Automated Weather Stations for Applications in Agriculture and Water Resources Management: Current Use and Future Perspectives

Proceedings of an International Workshop

Kenneth G. Hubbard and M.V.K. Sivakumar, editors
Automated Weather Stations for Applications in Agriculture and Water Resources Management: Current Use and Future Perspectives

Proceedings of an International Workshop
6–10 March 2000, Lincoln, Nebraska, USA

Editors
Kenneth G. Hubbard
and
M.V.K. Sivakumar

Sponsors
National Weather Service, USA
United States Department of Agriculture
High Plains Climate Center, University of Nebraska–Lincoln, USA
World Meteorological Organization

AGM–3
WMO/TD No. 1074

High Plains Climate Center, University of Nebraska–Lincoln, USA
and
World Meteorological Organization, 7bis, Avenue de la Paix
1211 Geneva 2, Switzerland
2001
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Foreword

Human societies have always been fascinated by weather and have learnt very quickly that, to produce food and to survive, they need to understand how the weather operates. Over the years, they learnt how to measure weather variables and how to use the information gained from the weather data in daily applications. Up until recently, the only way to observe weather and hydrological parameters was to take observations manually at set times during the day. Even today, in many countries, weather and hydrological observers painstakingly make these manual measurements and log the data carefully on observation sheets specially designed for this purpose. Data entry operators then enter these data on computers, and only after data quality control are the data made available for applications. This is a long process, and in some places for certain stations and parameters, it can take several months before these data are made available to user communities.

Today, in all countries there is a growing need for meteorological data in real or near-real time in support of a range of activities such as environmental monitoring, transport, agriculture, water resources assessment, manufacturing and construction industries, research and development, educational and recreational activities. The rapid evolution of microelectronics and computer and satellite technologies in the past two decades have quickly changed the way in which we record, exchange and store weather data. As a result, we now have the ability to not only observe weather and hydrological data on a near real-time basis but also to analyse them, develop applications and deliver products to users on a near real-time basis. It is generally recognized that the automation of surface weather observations can reduce costs, increase areal coverage and provide data at frequent intervals and for any observation time. Another advantage of automated observing systems is the accuracy of measurement for some parameters such as temperature and pressure and the ease with which data from multiple sites can be transmitted to a central processing site.

There is another strong argument for improved data collection through automated systems. Since the Earth Summit in Rio de Janeiro in 1992, three very important international Conventions have come into force, viz., the Convention on Biological Diversity (CBD), the United Nations Framework Convention on Climate Change (UNFCCC) and the United Nations Convention to Combat Desertification (UNCCD). Several countries have committed themselves to undertaking activities to implement these Conventions, which stress the importance of observational and monitoring networks to improve and strengthen existing capabilities of data collection, especially in the developing countries.

Furthermore, there is currently significant concern about the increasing impact of natural disasters, over 70% of which are weather- and climate-related. In addition, the projected global warming suggests a sharp increase in certain types of extreme weather events with negative impacts on agricultural production and water resources management. In order to develop strategies to cope with these extreme events, better data collection networks are needed in order to track their development, provide timely warnings and determine how climate change might be altering their frequencies and intensities. Automated weather stations in such networks can greatly improve the effectiveness of these tasks.
WMO, through its World Weather Watch (WWW), World Climate Programme (WCP) and Hydrology and Water Resources Programme (HWR), is pursuing a number of initiatives to take advantage of the technological developments in the areas of automated observing and telecommunications systems. Reports of two meetings on automatic weather stations, which were co-sponsored by WMO—the Expert Meeting on Requirements and Representation of Data from Automatic Weather Stations (De Bilt, Netherlands, April 1999) and the International Conference on Experiences with Automatic Weather Stations (Vienna, Austria, September 1999)—highlighted a number of issues related to automated weather measurements, and also stressed that surface point observations are crucial and will remain so into the foreseeable future for in situ calibration of satellite-borne sensors.

The WMO Commission for Agricultural Meteorology (CAgM) at its twelfth session, held in Ghana in 1999, recognized the rapid advancements made in the automation of weather data collection, computer technology in data archiving and management procedures. The Commission recommended that guidelines, consistent with those already laid down by the WMO Commission for Basic Systems (CBS), should be developed for automatic weather stations in agrometeorological settings. Such guidelines should be developed to maintain data quality and continuity, with particular attention being paid to regular maintenance and calibration of sensors. In the light of these considerations, the “International Workshop on Automated Weather Stations for Applications in Agriculture and Water Resources Management: Current Use and Future Perspectives” was held at the University of Nebraska from 6 to 10 March 2000. The Workshop was co-sponsored by the National Weather Service (USA); the United States Department of Agriculture; the High Plains Climate Center, University of Nebraska, Lincoln (USA); and the World Meteorological Organization.

I am pleased to note that the Workshop addressed a number of important topics related to automatic weather stations such as communication, site selection and network density, sensor performance and calibration, maintenance, quality assurance and network management, data management and data access, applications software and regional networks. I hope that the papers presented in this volume will serve as a very valuable source of information for all users of automated weather stations around the world.

G.O.P. Obasi
Secretary-General
World Meteorological Organization
Current Use of the Technology
Evolution of Automated Weather Station Technology through the 1980s and 1990s

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Abstract
The rapid development of automated weather stations (AWS) capable of remote operation and the establishment of several AWS networks during the late 1970s and early 1980s occurred because of new technologies from the electronics industry. The introduction of low-power CMOS components made operation from 12-volt direct current (DC) sources possible. The microprocessor, in addition to simplifying design, allowed on-site processing of AWS measurements, reducing data storage requirements. The current state and evolution of AWS sensors are discussed. Radiation errors in excess of 1.5°C can be expected at low wind speeds for air temperature measurements made in 12-plate unaspirated shields. Results of an RH sensor field intercomparison and a large sample of calibrations performed for one type of sensor verify the improvements in RH sensor design. Results of silicon cell pyranometer calibrations verify its use for many AWS applications. Wind effects on the catch of unshielded precipitation gauges can cause rainfall underestimations of up to 10% and for solid precipitation greater than 50%. Tipping bucket gauges, widely used in AWS, suffer additional errors with increased rainfall intensity. Advancements in soil moisture measurement technology argue for including this as a standard AWS variable. AWS network telecommunication options are reviewed and the potential for AWS access through the Internet are discussed.

Introduction
The development of digital AWS capable of remote, DC-powered operation occurred during the late 1970s. The usefulness to agriculture of more complete spatial coverage, increased sampling frequency, and timely reporting of climatological variables was well recognized, but the costs of implementing and maintaining early 1970s technology prevented widespread application. Existing digital recorders were not yet optimized for low-power operation over environmental temperatures; strip charts were the prevailing technology used for climatological recording. Today’s vast number of commercial AWS stands in sharp contrast to that of 25 years ago. Meteorological Research Inc.’s all-mechanical weather station provided one of the few operational options for sites without mains alternating current (AC) power.

Two innovations within the integrated circuit industry spurred the rapid development of environmental measurement instrumentation. The resulting flurry of commercial activity made available new capabilities at a cost that encouraged widespread application. The first of these was the development of CMOS logic integrated circuits (ICs) in the early 1970s. This technology greatly reduced the power requirements of electronics, making 12-volt battery operation practical for long-term field installations. The second was the introduction of the microprocessor in the mid-1970s. This innovation simplified the design of data
loggers, telecommunication peripherals, and sensors while providing greater sophistication and functionality. Within two years of microprocessor availability, RCA introduced the first CMOS processor and the capability to process measurements in the field became a reality. The advantages of on-site processing for AWS are discussed more fully below.

**Early AWS Networks**

Unencumbered by the design constraint of market competitiveness, the National Center for Atmospheric Research provided an early technological standard with their microprocessor-based Portable Automated Mesonet I (PAMI) in 1976 (Brock and Govind, 1977). PAMI supported up to 30 tower-based stations deployed over a 50-by-50 km area. The stations transmitted mean values every minute to a base using UHF radios. Other federal agencies during this time were developing networks capable of transmitting data over large distances. The Natural Resource Conservation Service’s (NRCS; previously the Soil Conservation Service) SNOTEL Network went operational in 1978 with 470 stations reporting mountain snowpack water equivalent and climate variables (Schaefer and Shafer, 1982). SNOTEL uses RF signals reflected from ionized meteor trails to transmit hourly values to locations up to 1300 km away. About 580 stations are in the network today. By 1980, the Bureau of Land Management had established the Remote Automated Weather Station (RAWS) network in the western United States using GOES satellites to transfer fire weather data to a ground station located in Boise, Idaho. Today the RAWS network exceeds 800 stations.

An early processing data logger optimized for agricultural and climatological networks was introduced in 1979 (Schimelpfenig et al., 1979). The CR2 Micrologger manufactured by Campbell Scientific, Inc. (Logan, Utah) had a one-minute (later a ten-second) scan rate, seven analog, and two pulse counting inputs. The logger stored slightly more than 600 processed values internally and supported remote data retrieval and system verification over voice-grade phone lines. More importantly, it operated for six months on eight alkaline D-cell batteries and over temperatures of -35° to 60° C.

The California Irrigation Management Information System (CIMIS) was one of the earliest U.S. networks established for crop water management (Snyder et al., 1985). CIMIS began operating in 1981 with 43 stations and currently has 98 (Ething and Moellenberndt, 1998). Shortly thereafter the Nebraska network was installed (Hubbard et al., 1983). Today, 136 AWS in seven midwestern states centralize their reports at the High Plains Regional Climate Center in Lincoln, Nebraska.

Although the justification and purpose for establishing AWS networks may vary, the basic operational requirements are common: (1) accurate measurement of meteorological variables, (2) timely access to the field data, (3) reliable operation with reasonable service costs, and (4) creation of a long-term record.

**AWS Functional Components**

The functional components common to all network stations include (1) electronic sensors, (2) system electronics, and (3) telecommunications hardware. The importance of the mast, sensor mounting hardware, enclosure, and power supply is noted but not discussed here.
Advances over the last 20 years have occurred in all areas, reducing the cost and logistics of long-term environmental measurement. Of the three, options for remote communication have grown the fastest.

Tanner (1990) discusses AWS functional components and considerations important to AWS operation. The attention given to on-site data storage and manual data retrieval testifies to the advancements in electronic storage media and wireless communication over the last 10 years. Brock et al. (1995) discuss the functional components of AWS in the design of a statewide network. The proposed ASAE Measurement and Reporting Practices for Automatic Agricultural Weather Stations (X505 Standards Proj., Comm. SW-244. ASAE, St. Joseph, Michigan) provides minimum recommendations for AWS operation.

The designs of AWS vary, with some having integral system electronics designed specific to the operational characteristics of the station, while others are configured around a more general-purpose stand-alone data logger. Regardless of the approach, minimum tasks required of the system electronics include (1) time keeping and measurement scheduling, (2) sensor signal conditioning and digital conversion, and (3) coordination of data transfer, whether site initiated or in response to an external request. More sophisticated systems may perform a number of additional functions.

The system electronics of today provide essentially the same functions as the early processor-based systems, but the performance capabilities have improved significantly. Memory capacity for operating systems (OS), programs, and data has increased 30 to 50 times while occupying less circuit board space. New OSs can now be downloaded from a PC instead of physically changing Programmable-Read-Only Memory. Processing and measurement speed has increased without significantly increasing power consumption. The integration of greater functionality in electronic components has simplified designs, reduced costs, and improved performance.

**On-site Processing**

At the time of the first microprocessors, options for on-site data storage were limited. Solid-state memory was expensive, with only a fraction of the capacity found in today’s ICs. Digital tapes, the largest-capacity media at that time, were unreliable at cold temperatures. Existing digital recorders stored a value per input channel every scan interval. As a consequence, scan intervals were frequently compromised to meet the data storage requirements. With processing data loggers, variables could be sampled at proper scan rates and the measurements compressed into results, such as means and extremes, for recording. This capability was significant in the evolution of AWS.

Additional benefits of on-site processing were signal values scaled to physical units, linearization of outputs from thermistors and soil moisture blocks, and sensor signals corrected for temperature sensitivity. Variables nonlinearly related to measurements could be averaged; for example, vapor pressure averaged from values computed for each RH and temperature measurement is a more correct estimate than that computed from mean RH and temperature. Conditional recording based on measurements or events became possible—for example, wind direction values discarded when wind speed is zero or rainfall intensity
obtained by recording the time of a specified accumulation. For those who have analyzed
strip chart recorded wind measurements, the ability to digitally record wind as a vector was
particularly significant. Mean vector magnitudes and directions and standard deviations of
direction, important for air quality diffusion models, were recorded directly in the field.

**Sensors**

System electronics and sensors require many of the same operating characteristics to be
successfully deployed in the field; accuracy, reliability, maintenance, power consumption,
and operating temperatures are concerns. For sensors, an understanding of the output signal
is also important to ensure compatibility with the data logger measurement capabilities. If
the measurement electronics do not accommodate the sensor signal, active external signal
conditioning is required. For example, high-gain differential amplifiers and reference junc-
tion temperatures are required for measuring thermocouples; precision voltage or current
excitations are needed for resistive bridges such as thermistors, platinum resistance ther-
mometers (PRTs), strain gauges, and wind vane potentiometers; and low-level AC frequen-
cies from anemometers require appropriate pulse circuitry.

Sensors commonly used in AWS, hydrology, and other environmental applications can be
grouped into two general classes: passive or active. Passive sensors do not contain active
circuitry; they are electronically simple and require little or no power. (This definition
varies from those classifying sensors needing an excitation voltage as active—e.g., ther-
mistors.) A number of commonly used AWS sensors are passive: silicon cell and thermo-
pile type pyranometers, thermistors and PRTs, cup anemometers and wind vanes, and tipp-
ing bucket rain gauges.

Traditionally, AWS sensors requiring active circuitry are those where the response of the
fundamental sensing element does not directly produce an easily measured signal. Polymer
film relative humidity (RH) sensors are an example, where the capacitance of the polymer
chip is converted to a voltage signal. The circuitry may also compensate the signal for
temperature effects on the chip's response to RH. Active circuitry may be included with a
passive sensor to provide other benefits. Consider submersible pressure transducers de-
ployed in deep bore holes. The pressure transducer is passive, being a full resistive bridge,
but versions are available that contain their own voltage reference and convert the bridge
signal to a frequency, 4-20 mA, or digital output. These types of conditioned signals avoid
problems associated with long lead lengths and the sensor requires only an unregulated 12-
volt source for operation.

Over the last 20 years, new active sensors have incorporated processors, taking advantage
of lower costs, simpler designs, and increased functionality. Whereas early “smart” sensors
generally implied a digital RS-232 output, a number of today’s processor-based sensors
provide standard analog or frequency output signals compatible with conventional mea-
surement systems. Non-processor-based active sensors are still widely available, but are
being replaced by smart designs.

Smart sensors apply the same techniques to improve sensor performance as those used in
processing data loggers—i.e., self-calibration, corrections for calibration nonlinearity, tem-
perature compensation, noise filtering, and scaling results to engineering units. In more
complex systems, diagnostics are provided. Barometers, RH sensors, acoustic anemometers, soil moisture sensors, water quality sensors, and submersible pressure transducers are all examples having improved sensor performance with microprocessors. The measurement requirements for some of the AWS variables, however, continue to be met with relatively simple sensors whose performance would improve little with microprocessors.

The RS-232 electrical interface continues to be the most common standard for sensors providing digital outputs, with the RS-422 and multidrop RS-485 interfaces seeing increased availability. In general, these interfaces were not developed with environmental applications in mind and in 1988, at the suggestion of the U.S. Geological Survey, the SDI-12 interface for environmental sensors was developed (SDI-12 Support Group, 2000). The SDI-12 standard includes a communication protocol and conservatively provides for distances of up to 60 m between the sensor and the measurement electronics. The interface has been implemented by a number of sensor manufacturers, primarily in the United States and Canada.

Characteristics of meteorological sensors and sources of problems are provided by WMO (1996). Sensors for AWS and a list of manufacturers are given by Tanner (1990), and many of the principles discussed by Fritschen and Gay (1979) relating to environmental sensors are still useful. A summary of the state of AWS sensors and the quality of climatological measurements today as compared to 20 years ago would include: (1) Sensors for solar radiation, air and soil temperature, and wind have changed little; the measurements then and now are of sufficient quality for most applications. (2) Relative humidity sensors have improved greatly and provide satisfactory measurements for most applications. (3) The use of effective, low-power aspirated shields would reduce errors in temperature and RH measurements. (4) Measurements from unshielded tipping-bucket gauges systematically underestimate rainfall amounts. (5) Solid precipitation remains the most inaccurately measured standard AWS variable, and solutions for obtaining snowpack water equivalent are still needed. (6) Innovations have occurred in wind measurement with the development of several acoustics models designed to replace cup and vane technology. (7) Reasonable options for long-term soil moisture measurement did not exist 20 years ago. The improvement in sensors (see www.sowacs.com) now warrants its consideration as a standard AWS measurement.

**Field Uncertainty of AWS Measurements**

The uncertainty or error $E$ of a measurement $X_m$ is its departure from the true value $X$, as given by $E = X_m - X$. Sources contributing to AWS measurement uncertainty include measurement system and sensor errors, sensor sampling errors, and sensor operating limitations. Improper station siting causes inaccuracies in representing the local climate but is not a source of measurement uncertainty.

With few exceptions, errors contributed by today's measurement systems are several times smaller than the uncertainties specified for AWS sensors. Fraden (1993) summarizes several sensor characteristics that can contribute to errors in the response of the sensor to the variable of interest. Calibration drifts are one of the most common found in AWS sensors deployed for long time periods. Another is response time. An example is the characteristic lag of polymer film RH sensors when humidity changes from high to low values.
The erroneous value reported by a cup and vane anemometer immobilized with rime ice or frozen rain is due to an operating limitation. Data quality procedures can screen these measurements, but wind speeds reported by an iced, rotating anemometer are impossible to correct. Anemometer bearings packed with dust; RH sensor filters contaminated with sea-salt particles; and pyranometers, 12-plate shields, and rain gauge orifices covered, packed, or bridged with snow all produce incorrect measurements because of sensor operating limitations.

Sampling errors are those associated with sensor deployment and sampling methods. They include those where the introduction of the sensor alters the environment being measured or where the measurement is not adequately isolated from other environmental disturbances. Radiation errors in air temperature measurements are often greater than the measurement electronics and sensor uncertainties combined. Heat conduction along sensor lead wires influences soil and air temperature measurements. Wind flow distortion over a precipitation gauge interferes with the catch, causing underestimation of precipitation.

**Radiation Errors in Air Temperature Measurements**

Naturally ventilated shields are commonly used in remote AWS. Reasons for this include the expense and power consumption of aspirated shields, the fact that larger errors are possible with poorly designed aspirated shields, and, in many cases, acceptance of the error with respect to the designated applications. The R.M. Young Co.'s (Traverse City, Michigan) Model 41002 12-plate shield is widely used in the United States. Richardson et al. (1999) provide a useful investigation of the shield using ray tracing, flow simulation, and wind tunnel techniques. Table 1 summarizes the difference at low wind speeds found by Tanner et al. (1996) between two 12-plate shielded sensors and an aspirated thermocouple. For reference, well-designed aspirated shields limit radiation errors to 0.1–0.2°C over most surfaces. Radiation errors include both an overestimation from solar loading and an underestimation on clear nights due to radiative cooling. The positive errors shown for nighttime are caused by the shield lagging air temperature following sunset. The Vaisala (Woburn, Massachusetts) Model HMP35C RH chip and thermistor are enclosed in a protective Teflon membrane, further restricting the airflow about the thermistor. This might explain the slightly larger errors found for the HMP35C than for the Campbell Scientific (Logan, Utah) Model 107 thermistor probe. The measurements summarized in Table 1 were made over a grass surface. Temperatures measured with naturally ventilated shields over snow surfaces can have errors approaching 4–5°C in calm conditions.

**Relative Humidity**

Twenty years ago, options for long-term measurements of atmospheric water vapor were unsatisfactory (McKay, 1978). Historically, the mechanical hair hygrometer and strip chart recorder have been widely used for unattended RH measurements. The prevalent technology most suited to electronic recording has been the wet- and dry-bulb psychrometer, the primary sensor used in many parts of the world today.

The relationships between wet- and dry-bulb temperatures and vapor pressure are well verified; properly designed and operated systems provide accurate estimates at relatively low costs for many conditions. In the late 1970s WMO adopted a psychrometer as an international reference standard for meteorological measurements above 0°C (Wylie and
Table 1. Radiation errors at low wind speeds for two models of air temperature sensors installed in naturally ventilated 12-plate shields (R.M. Young Model 41002). Errors are differences of 15-minute mean values from those obtained with a small aspirated thermocouple. Errors shown for clear-day, overhead sun angles and at night.†

<table>
<thead>
<tr>
<th>Wind speed m s⁻¹</th>
<th>800–1000 Wm⁻² radiation$</th>
<th>Nighttime#</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HMP35C¶</td>
<td>CSI 107¶</td>
</tr>
<tr>
<td>0 to 1</td>
<td>1.8 to 0.6</td>
<td>1.2 to 0.4</td>
</tr>
<tr>
<td>1 to 2</td>
<td>1.3 to 0.4</td>
<td>0.7 to 0.2</td>
</tr>
<tr>
<td>2 to 3</td>
<td>0.8 to 0.3</td>
<td>0.4 to 0.2</td>
</tr>
</tbody>
</table>

† Error ranges for respective wind speed classes are summarized from Tanner et al., 1996, pp. 227–230.
‡ Errors shown do not include the sensor’s uncertainty of ±0.4°C over a -24 to 48°C range because sensors were calibrated to an uncertainty of ±0.05°C before field tests; operational uncertainty would include sum of radiation errors and sensor uncertainty.
§ Component of radiation measured normal to horizontally level pyranometer; solar loading by radiation reflected from underlying grass surface is not included.
¶ Vaisala (Woburn, Massachusetts) Model HMP35C RH and temperature sensor contains the same thermistor as used in Campbell Scientific’s (Logan, Utah) Model 107 sensor.
# Negative errors are due to long-wave radiative cooling of shield below air temperature; positive errors are due to thermal inertia of shield as air cools following sunset.

Lalas, 1981 and 1992). In spite of their simplicity and apparent virtues, psychrometers are not well suited for AWS networks. In general, considerable maintenance is necessary to achieve high accuracies. Personal inspection of both aspirated and naturally ventilated field psychrometers at several locations leads the author to conclude that the relatively simple operating principles are interpreted as an absolution from field service. Their operation at temperatures below freezing is a problem and they must be properly ventilated, requiring power. A wetted clean surface is needed to achieve equilibrium evaporation at wet-bulb temperature. The principles of psychrometry and an analysis of their error sources are given by Tanner (1972).

The stability, durability, and response of polymer film RH sensors have improved to the point that field accuracies of ±5% RH over broad RH and temperature ranges are a reasonable expectation. Tables 2 and 3 show field measurements conducted by Campbell Scientific, Inc., from September 1997 through September 1998 on four models of replicated sensors. All the sensors detect the capacitance of a polymer film chip as it responds to absorbed water vapor. The Model 50Y from Vaisala, Inc. (Woburn, Massachusetts) and Model HP043 from Rotronics Instrument Corp. (Huntington, New York) are lower-cost sensors than the HMP35 or HMP45.
The sensors were calibrated at 20, 50, and 90% RH indoors before deployment and checked again, but not adjusted, after six months in the field. Final calibrations were performed at the end of the intercomparison. For each sensor and humidity range, a single value is shown. This value is the average of all 15-minute means over a month falling within the given humidity range. Values for Table 2 are at temperatures below 0°C in December, four months after deployment. Table 3 presents values at temperatures above 15°C from July, when the sensors had been in the field for 11 months. The number of 15-minute means in the specified RH and temperature classes are given in the second row from the bottom; the last row is the mean temperature.

The comparisons within a sensor type and across all sensors are rather remarkable, given the range of conditions. Overall intra-sensor disagreement is somewhat greater at cold temperatures (Table 2), the largest being 2.7 (40–70% RH) and 2.3 (70–90% RH) for the Model 50Y. At warmer temperatures (Table 3), the maximum intra-sensor disagreement is only 1.3 (70–90% RH) and 2.8 (above 90% RH) for the HP043s. Across all sensors, disagreement is again greatest at colder temperatures, with maximum departures of 8.3 (40–

<table>
<thead>
<tr>
<th>RH Ranges</th>
<th>0–40</th>
<th>40–70</th>
<th>70–90</th>
<th>L.T. -15°C</th>
<th>G.T. 90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HMP35C†</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 1</td>
<td>33.6</td>
<td>63.1</td>
<td>82.8</td>
<td>91.4</td>
<td></td>
</tr>
<tr>
<td>No. 2</td>
<td>33.7</td>
<td>62.0</td>
<td>81.8</td>
<td>90.3</td>
<td></td>
</tr>
<tr>
<td>HMP 45C†</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>No. 1</td>
<td>35.3</td>
<td>66.4</td>
<td>85.0</td>
<td>93.0</td>
<td></td>
</tr>
<tr>
<td>No. 2</td>
<td>35.6</td>
<td>67.1</td>
<td>85.5</td>
<td>93.2</td>
<td></td>
</tr>
<tr>
<td>50Y †</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 1</td>
<td>36.4</td>
<td>70.3</td>
<td>85.7</td>
<td>92.8</td>
<td></td>
</tr>
<tr>
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<td>35.4</td>
<td>67.6</td>
<td>83.4</td>
<td>92.5</td>
<td></td>
</tr>
<tr>
<td>No. 3</td>
<td>35.6</td>
<td>67.8</td>
<td>84.0</td>
<td>93.4</td>
<td></td>
</tr>
<tr>
<td>HP043‡</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 1</td>
<td>—</td>
<td>67.3</td>
<td>82.0</td>
<td>87.6</td>
<td></td>
</tr>
<tr>
<td>No. 2</td>
<td>35.3</td>
<td>66.2</td>
<td>81.6</td>
<td>86.9</td>
<td></td>
</tr>
<tr>
<td>No. 3</td>
<td>35.8</td>
<td>67.4</td>
<td>82.6</td>
<td>88.2</td>
<td></td>
</tr>
<tr>
<td>No. of 15-min. means</td>
<td>62</td>
<td>109</td>
<td>696</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Mean temperature, °C</td>
<td>-2.6</td>
<td>-4.4</td>
<td>-7.0</td>
<td>-15.9</td>
<td></td>
</tr>
</tbody>
</table>

† Vaisala, Inc., Woburn, Massachusetts.
‡ Rotronic Instrument Corp., Huntington, New York.
Table 3. High temperature field intercomparison of four RH sensor models with replication; values are monthly means of 15-minute mean values occurring in one of four RH ranges and two temperature ranges.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>G.T. 25°C 0–40</th>
<th>RH Ranges 40–70</th>
<th>15 to 25°C 70–90</th>
<th>G.T. 90</th>
</tr>
</thead>
<tbody>
<tr>
<td>HMP35C†</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 1</td>
<td>27.2</td>
<td>55.6</td>
<td>78.4</td>
<td>94.5</td>
</tr>
<tr>
<td>No. 2</td>
<td>27.6</td>
<td>55.8</td>
<td>78.2</td>
<td>93.8</td>
</tr>
<tr>
<td>HMP45C†</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 1</td>
<td>25.8</td>
<td>55.8</td>
<td>78.0</td>
<td>92.7</td>
</tr>
<tr>
<td>No. 2</td>
<td>26.0</td>
<td>56.1</td>
<td>78.2</td>
<td>92.9</td>
</tr>
<tr>
<td>50Y†</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 1</td>
<td>27.6</td>
<td>56.4</td>
<td>77.9</td>
<td>92.3</td>
</tr>
<tr>
<td>No. 2</td>
<td>26.9</td>
<td>56.1</td>
<td>77.8</td>
<td>92.3</td>
</tr>
<tr>
<td>No. 3</td>
<td>27.2</td>
<td>56.5</td>
<td>78.3</td>
<td>93.0</td>
</tr>
<tr>
<td>HP043‡</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 1</td>
<td>26.8</td>
<td>54.8</td>
<td>76.3</td>
<td>91.2</td>
</tr>
<tr>
<td>No. 2</td>
<td>27.0</td>
<td>55.4</td>
<td>77.6</td>
<td>94.0</td>
</tr>
<tr>
<td>No. 3</td>
<td>27.3</td>
<td>55.6</td>
<td>77.1</td>
<td>92.6</td>
</tr>
<tr>
<td>No. of 15-min. means</td>
<td>914</td>
<td>973</td>
<td>357</td>
<td>67</td>
</tr>
<tr>
<td>Mean temperature, °C</td>
<td>30.2</td>
<td>20.4</td>
<td>18.2</td>
<td>17.7</td>
</tr>
</tbody>
</table>

† Vaisala, Inc., Woburn, Massachusetts.
‡ Rotronic Instrument Corp., Huntington, New York.

70% RH, HMP35C No. 2 and 50Y No. 1) and 6.5 (above 90% RH, 50Y No. 3 and HP043 No. 2). At warmer temperatures, sensor agreement is within 3.3% RH for all humidity ranges.

The stability or drift claimed for some of today’s polymer film sensors has improved, being better than 1% RH change per year. Where sensors have been returned more than once to Campbell Scientific, Inc., for calibration, the time interval can be determined, and an “annual stability” computed. Figure 1 shows the annual drift error at 20, 50, and 90% RH for nearly 290 sensors. Nothing is known about the sensor’s field exposure time or conditions. Almost 58% were returned between one and two years and 19% between three and four years. At 90% RH, 55% percent of the samples shown in Figure 1 are within ±1% RH yr⁻¹ and nearly 83% are within ±2% RH yr⁻¹.

The calibrations are performed at room temperature using LI-COR’s (Lincoln, Nebraska) Model 610 Dew Point Generator. The dew point is controlled to provide fixed RH values by measuring each sensor’s temperature in the calibration air stream and ensuring that
gradients do not exist. The accuracy of the dew point generator is specified as ±0.2°C and the uncertainty of the sensor temperature, including gradients, is within ±0.2°C. These combine to give a root-sum-of-squares uncertainty of 0.4% RH at 20% RH, 0.9% RH at 50% RH, and 1.6% RH at 90% RH. The distribution in Figure 1 does not reflect the calibration uncertainty or the ±0.5% RH practical tolerance for adjusting the sensor; however, the results provide limits on expected drift determined from experienced operation and are a dramatic improvement over RH sensors of 20 years ago.

The error distribution at room temperature for a large number of HMP35Cs returned for calibration is shown in Figure 2. Vaisala specifies a ±2% RH error over 0 to 90% RH and a ±3% error from 90 to 100% RH, at 20°C. The field exposure or time since previous calibration is not known, but a number of the sensors included in Figure 2 exceed three years on both accounts. The information characterizes the drift experienced with field sensors. The graph shows a slight positive skew with 43% of the probes at 90% RH reading high by 5% RH or less and 36% reading low by this amount. At 50% RH, 53% of the sensors have errors up to 5% RH, while only 28% are low by this bound. At 20% RH, 78% of the sensors are within ±2.5% RH.

**Solar Radiation**

State climatological networks in the United States have historically measured solar radiation more actively than federal programs because of its importance to agricultural studies.
and evaporation. The two most prevalent pyranometer technologies are thermopile devices and the lower-cost silicon photocell. Thermopile pyranometers are equipped with either one or two glass domes having a relatively flat spectral transmissivity from about 300 to 2800 nm. Performance criteria for thermopile pyranometers and their classifications are given by WMO (1996) and ISO (1990), but the requirements for uniform spectral sensitivity preclude classification of the silicon photocell.

The uneven spectral response of photocells covering the 400 to 1100 nm region of the solar spectrum requires that they be used only under the spectral conditions for which they are calibrated. This prevents their use for careful work within vegetation canopies or for measuring reflected radiation. The uniformity of the daylight spectrum under most sky conditions is such that well-designed silicon photocells measure hourly and daily radiation totals with accuracies comparable to first-class instruments (i.e., typically better than 5%, with maximum errors of 5 to 8%). Additional error is possible if the site elevation and atmospheric water content vary greatly from calibration conditions (e.g., a high-elevation desert). On-site comparison with a calibrated thermopile pyranometer corrects this problem.

LI-COR's (Lincoln, Nebraska) Model 200S and Kipp and Zonen’s (Delft, Netherlands) Model SP LITE are two examples of photocell pyranometers suitable for most AWS applications. A stability of less than 2% change per year is specified for the Model LI200S. Figure 3a shows the time between calibrations for 520 Model LI200Ss. Intervals for about
70% of the sensors are fairly evenly distributed between two and six years. Figure 3b shows the percent sensitivity error per year using the original calibration. Nearly 86% of sensors are within specification; of these, 66.5% show an increased sensitivity, requiring a smaller calibration coefficient. The inexpensive silicon cell pyranometer has been used for many years, providing a cost-effective solution for radiation measurements.
Precipitation

The national precipitation networks in most countries still rely on manual observations. The two types of electronic gauges most commonly found in unattended AWS use either a weighing mechanism or a tipping bucket. The latter prevail in U.S. climatological networks because of their lower cost and simplicity. Weighing gauges are two to three times the cost of tipping-bucket gauges, but their accuracy does not depend on rainfall intensity and their resolution is limited only by the mechanical sensitivity of the platform and displacement sensor. Automated measurements make possible the recording of rainfall intensity, an important variable for hydrologic, soil erosion, and water quality models.

Total rainfall is often regarded as one of the more straightforward AWS measurements because of the simplicity of the gauges, yet inaccuracies exist that are difficult to quantify and systematically correct. The high spatial variability of precipitation influences the level of uncertainty tolerated in its measurement. Estimates of solid precipitation in colder climates remain one of the most inaccurate of all automated measurements.

Underestimation of precipitation caused by wind and affecting both manual and automatic gauges is well documented. Using data from three WMO Solid Precipitation Measurement Intercomparison (SPMI) sites, Yang et al. (1998) compared results from the manual U.S. National Weather Service (NWS) 8-in. standard gauge with the Intercomparison reference. Catch ratios (NWS 8-in. gauge/reference gauge, %) for different precipitation types were fit to mean daily wind speeds (Figure 3, Yang et al., 1998). Table 4 shows catch ratios picked at 2 and 5 m s⁻¹ wind speeds for alter-shielded and unshielded gauges. Although for any singular event the catch ratio functions have significant uncertainty, Table 4 documents the influence of wind on precipitation measurements. These are: (1) for all but the lowest wind speeds, catch ratios are lower for unshielded gauges than for shielded, (2) even rainfall is subject to significant errors, and (3) even with shielded gauges, errors of 40–50% can occur in snowfall catch at wind speeds of 5 to 10 m s⁻¹.

Unshielded tipping-bucket gauges are operated in a number of U.S. AWS networks. In addition to the wind errors, tipping bucket gauges underestimate rainfall at higher intensities. For a given receiver area (catch orifice), this error worsens for smaller bucket volumes (i.e., higher resolution gauges). Using simulated rainfall rates, Humphrey et al. (1997) studied

<table>
<thead>
<tr>
<th>Catch Ratio</th>
<th>2 m s⁻¹ wind speed</th>
<th>5 m s⁻¹ wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shielded</td>
<td>Unshielded</td>
</tr>
<tr>
<td>Rain</td>
<td>94</td>
<td>92</td>
</tr>
<tr>
<td>Mixed</td>
<td>91</td>
<td>86</td>
</tr>
<tr>
<td>Snow</td>
<td>90</td>
<td>70</td>
</tr>
</tbody>
</table>

† Source: Figure 3, Yang et al., 1998.
20.3 cm (8 in.) receiver diameter gauges having 1, 0.2, and 0.1 mm resolutions (see Figure 5 in Humphrey et al., 1997). The 0.1 mm resolution gauges showed errors of 15, 19, and 27% at rainfall intensities of 50, 100, and 200 mm h⁻¹, respectively. The 0.2 mm resolution gauges used in the study underestimated by 10, 13, and 15% at the respective intensities, and those with a 1 mm resolution showed errors of 7, 7.5, and 8.5%. Although the 1 mm gauge has the smallest errors, the larger bucket volume can miss trace precipitation events and is subject to larger evaporation errors. WMO (1996) specifies a minimum of 0.2 mm resolution for careful work. Tipping-bucket gauges equipped with a siphon deliver a measured amount of water to the bucket independent of rainfall intensity. Hydrological Service’s (Sydney, Australia) Model TB-3, for example, not included in the above study, has a 0–500 mm h⁻¹ measurement range and specifies an accuracy of better than 2% at 100 mm h⁻¹.

In many regions, solid precipitation is an important component of the hydrologic cycle, and better measurement practices and techniques are still needed. The WMO SPMI (Goodison et al., 1998) confirmed that gauge accuracies can be improved greatly with appropriate shielding, and that reliable solid precipitation estimates can be obtained by correcting for wind errors. The SPMI Organizing Committee designated the 12 m diameter octagonal double fence (4 m diameter inside fence) surrounding a shielded manual Russian gauge (Tretyakov) as their Double Fence Intercomparison Reference (DFIR). The DFIR has been recommended to the WMO as a secondary reference for solid precipitation measurements.

These results, although encouraging, were obtained with careful observations from manual gauges at attended sites and do not represent the problems confounding unattended, automated measurements. Goodison et al.‘s report (1998) includes experiences with automated gauges operated during the SPMI. Capping of the receiver, build-up on the orifice walls, and evaporation from heated gauges all degrade the recorded totals and timing of solid precipitation measurements. Antifreeze-charged shielded gauges, whether weighing, level detection, or tipping-bucket types (McCaughey and Farnes, 1996; Carcoana and Enz, 2000), presently represent the most reasonable options, but catch ratio corrections for wind errors are required. Heated tipping-bucket gauges are specifically not recommended for use in regions where temperatures are below 0°C for extended periods (Goodison et al., 1998).

The NRCS has used snow pillows to measure the snowpack water equivalent directly for more than 20 years at their SNOTEL sites. The expense, maintenance, and unique set of measurement problems associated with snow pillows makes them an unlikely solution for most climatological networks. More recently, commercialization by Canberra Industries Inc. (Meriden, Connecticut) of a product developed at the U.S. Sandia National Laboratories warrants cautious optimism (Osterhuber et al., 1998). The Canberra Snow Pack Monitor measures cosmic gamma radiation above the snowpack and at ground level, relating the attenuation to snowpack water equivalent. The preliminary estimates of cost are significantly less than previous similar technologies.

**Telecommunications**

Of the three AWS functional components, options for remote communications have advanced the fastest (Table 5). In addition to the innovations occurring with wireless technology, Internet communication with AWS is now a reality, constrained only by Internet access at the site. Network communication schemes using single frequency, one-way transmission
Table 5. Selected performance characteristics showing tradeoffs for various AWS RF communication options. †

<table>
<thead>
<tr>
<th>Technology</th>
<th>Receive current</th>
<th>Transmit current</th>
<th>Range</th>
<th>Data throughput‡</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>km</td>
<td>kbps</td>
</tr>
<tr>
<td>Cell phone (analog)</td>
<td>0.170</td>
<td>1.5–2.0</td>
<td>§</td>
<td>4.8</td>
</tr>
<tr>
<td>Cell phone (digital)‡</td>
<td>0.02</td>
<td>0.2–0.5</td>
<td>¶</td>
<td>9.6</td>
</tr>
<tr>
<td>VHF/UHF</td>
<td>0.05</td>
<td>1–2</td>
<td>30</td>
<td>2–3</td>
</tr>
<tr>
<td>Spread spectrum</td>
<td>0.02–0.10</td>
<td>0.5–0.8</td>
<td>25</td>
<td>10–100</td>
</tr>
<tr>
<td>ELOS#</td>
<td>0.07</td>
<td>20††</td>
<td>80–125</td>
<td>††</td>
</tr>
<tr>
<td>Meteor burst#</td>
<td>0.07</td>
<td>20††</td>
<td>1600</td>
<td>4‡‡</td>
</tr>
<tr>
<td>Inmarsat-C</td>
<td>0.9</td>
<td>10</td>
<td>§§</td>
<td>0.6–1.2</td>
</tr>
<tr>
<td>GOES satellite</td>
<td>0.01</td>
<td>2.2</td>
<td>¶¶</td>
<td>¶¶</td>
</tr>
<tr>
<td>ARGOS satellite</td>
<td>0.00</td>
<td>0.6</td>
<td>#</td>
<td>#</td>
</tr>
</tbody>
</table>

† Values are representative and meant for relative comparison; values will vary for different products and configurations (e.g., current and range will vary with transmitted power).
‡ Data throughput is often less than specified bit rates because of message headers, error correction bits, routing information, etc.
§ Distance to cell tower for successful operation varies widely with provider; 12–22 km is a rough approximation.
¶ GSM (global system for mobile communication) is used extensively in Europe and Australia; absolute range from cell tower is about 25 km. Qualcomm Inc.’s (San Diego, California) CDMA (code division multiple access) is predominant in the United States; operating range from cell tower can be 80–100 km.
# Meteor Communications Corp., Kent, Washington.
†† Remote station transmits 100 ms pulse when clear link to base is identified; typical duty cycle for ELOS is 1 pulse per s, with about 100 data bytes per pulse with 9.6 kbps rate.
‡‡ Probability of ionized meteor trails is a function of the earth’s diurnal and annual cycle; typical number for data throughput is 256 bits every five minutes, 95% of the time.
§§ Worldwide coverage to 70° latitudes.
¶¶ Coverage over western hemisphere to 70° latitudes. Using the present data rate of 0.1 kbps and a typical 30 s transmission every four hours (1 min access with 15 s guard intervals), data throughput is 708 bytes per day. NOAA–NESDIS is in the process of upgrading to 300 and 1200 bps data rates but will probably reduce transmit times proportionally. Exact timing through implementation of GPS receivers in GOES transmitters will provide greatest increase in data throughput by eliminating guard intervals.
### Polar satellites with worldwide coverage; maximum data throughput is a function of latitude, for example, about 864 bytes at 30° and 1536 at 55°.
from the AWS require either time multiplexing of the reporting intervals, such as with the GOES satellites, or multiple transmissions of the same message at either random or even intervals. Interrogated networks with two-way communication detect improperly received messages and request retransmissions. Additionally, system diagnostic checks and even program changes can be performed remotely. On-site data storage in the logger prevents loss of data during temporary communication failures.

Factors determining the communications technology suitable for an AWS network are (1) station distance, (2) site access, (3) data density, and (4) reporting frequency. Phone communication, for example, is not the optimal choice for 15-minute reporting because of the time required to establish a connection and the expense of long-distance charges. However, daily reporting of hourly processed values is adequate for most climatological networks, and standard voice-grade telephone lines provide a simple, reliable means. Cellular phone use in the United States has increased with cell coverage, allowing siting of stations in locations previously inaccessible with land lines.

Radio frequency (RF) networks, whether conventional VHF or UHF or spread spectrum, offer high-density, local area monitoring with near real-time reporting capability. Communication is limited to "line-of-sight" ranges, typically 25 to 35 km. Where individual stations can serve as repeaters to more distant stations, greater coverage is possible. Using lower frequencies, Extended Line-of-Site (ELOS) such as offered by Meteor Communications Corp. (Kent, Washington) can extend communication distances to greater than 130 km.

RF networks can be accessed from anywhere through a phone-to-RF base station or, more recently, through the Internet if local access is available. The value of a wireless extension to a dedicated network is demonstrated by the Oklahoma Mesonet (Brock et al., 1995), where more than 100 bytes of data are retrieved every 15 minutes from each of 115 AWS spread over a 178,000 km² area. The remote stations are accessed by VHF radios interfaced to a statewide law enforcement network at terminals located in each county.

Proliferation of technologies supporting the Internet provide a unique option for AWS communication. Internet service local to the AWS is required, and also a tolerance to the timing variability of delivered information packets. If, for example, the remote terminals of the dedicated system used by the Oklahoma Mesonet were replaced by an Internet site, the remote AWS could be accessed as at present by interfacing the existing VHF radio to the Internet. The response, whether accessing a remote station or delivering data to the Mesonet central facility, would probably degrade from that of the present system depending on the Internet load. For networks accessing stations once a day with long-distance phone calls, the Internet could be used to initiate local calls through a phone modem interfaced to the Internet through a micro-serial server. Recent CDPD (cellular digital packet data) technology provides wireless access to the Internet at rates of up to 19.2 kbps. Present coverage in the United States is too sparse to be used generally for AWS networks. Where coverage does exist, the Internet has been used to successfully communicate and retrieve data from a remote data logger.
Use of telecommunications options such as quality land-line telephones, cellular phones, and the Internet are limited to those regions maintaining the necessary infrastructure. These options, therefore, are not global solutions and the use of national satellites such as GOES, Meteosat, and Argos; private satellite data services such as Inmarsat; and meteor burst communication must be considered. Operational costs of data retrieval vary widely for these technologies. For those obtaining access to GOES, data retrieval is essentially free; so is meteor burst communication after the initial investment for the receiving station. Costs per station for Inmarsat and Argos, however, may be US$20–$30 per day for typical climatological applications.

References


Lessons from the North American Experience with Automated Weather Stations

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Abstract
Automated weather station networks (AWSN) have become commonplace in North America over the past 25 years. During this period, network operators have collectively learned a number of important lessons relative to operating AWSN. Among the lessons learned, the need for effective network planning is perhaps the most important. Other important lessons include the need for well-defined network objectives, effective quality control strategies, useful products/information, adequate funding, and flexibility in dealing with changing clientele. Challenges that AWSN operators must address in the future concern data redundancy, growing meteorological databases, affiliations with agricultural experiment stations, integrating remote sensing products, changes in clientele, improving data quality control, standardizing computation procedures, and upgrading equipment.

Introduction
The advent of cost-effective microprocessors during the 1970s revolutionized the field of data acquisition and led to the development of a new generation of automated weather stations. This new digital technology made acquisition of meteorological data at remote sites more reliable and cost effective and led to the proliferation of automated weather station networks (AWSN) for purposes ranging from management of agricultural systems to assessment of hazardous meteorological conditions. An extensive knowledge base has developed from the operation of AWSN over the past 25 years. In this chapter, we summarize some of the important lessons learned from the North American experience with AWSN, and then conclude by presenting some challenges facing AWSN in the future.

Lessons Learned

Lesson 1. Good Planning Is Essential
Planning is perhaps the most important aspect of developing and then operating an AWSN. Planning should begin at network inception and continue throughout the life of a network. A written plan should be completed before network development begins. This initial plan should first outline the objective(s) or product(s) of the proposed AWSN. Establishment of network objectives provides important guidance on many elements of AWSN, including the types of equipment and sensors used; station siting and density; data retrieval, processing, and quality control procedures; costs; and possible cooperators. The written plan should provide details on each of these elements as well as provide time lines for network development, an explanation of how the network will function when opera-
tional, projected development and operating costs, and potential funding sources for de-
velopment and operations. Advisory committees consisting of potential cooperators and/
or users of network information can provide valuable assistance in plan development.

An essential outcome of the final network plan is to identify cooperators, sponsors, and
volunteers that will assist with network development and operation. It is advisable to
have some form of written agreement indicating the level of support (e.g., funding, per-
sonnel, equipment) the network can expect from these individuals/entities. Failure to
firmly identify these network partners can lead to costly inefficiencies when developing
and operating a network.

Effective planning is also essential for general network operations. It is generally advis-
able to develop an annual operating plan for an AWSN that details budgets, personnel
needs, product improvement/development plans, changes in network operation, and pub-
lic education efforts.

Lesson 2. Educate Your Superiors
There are few if any stand-alone AWSN. Most AWSN are embedded in some organiza-
tional structure, which means network personnel report to higher-level administrators.
All too often administrators believe that an AWSN requires a one-time infusion of fund-
ing to develop the network and that once developed, the network can run on its own with
limited personnel and funding. Network operators of course recognize this is a false im-
pression, but many operators do a poor job of educating their superiors about the realities
of running a network. It is important to educate administrators that running a weather
network is not a part-time job and that networks have both developmental and operating
costs. Operating costs are chronic and often cannot be covered with user fees/service
subscriptions and therefore require some form of subsidy. Operators must also recognize
that administrators and bureaucracies change rather frequently, and they must be willing
to reeducate their superiors on a regular basis.

Lesson 3. Station Siting and Network Density Depend on Network Objectives
Weather networks have been established for a variety of purposes, including general cli-
mate assessment, agricultural pest management, predicting crop water requirements, and
transportation safety. No one siting criterion works for all types of networks. Networks
with a single objective, such as transportation safety or predicting agricultural disease
outbreaks, often have strict siting requirements or recommended station densities. Net-
works with multiple objectives may have less stringent siting and density requirements,
or may contain a blend of stations with differing siting requirements. Often, users other
than the network’s targeted audience will want to use the data for purposes unrelated to
network objectives. Network operators need to be honest and frank with these users re-
garding the limitations of their data set for unintended uses.

Lesson 4. Funding is a Chronic Problem
Most automated weather networks are operated by government agencies or universities
and receive a relatively high operational subsidy. Personnel is the network cost most often
subsidized. For example, the Arizona Meteorological Network (AZMET), a small agri-
cultural network in Arizona, receives 90% of its personnel budget or ~70% of its total operating budget from the University of Arizona. User fees and grants/contracts provide the remaining 30% of AZMET’s budget. Many other networks report subsidies of the same percentage magnitude. The 1990s was a decade in which government expenditures received intense scrutiny, and many automated weather networks struggled to survive because of their heavy reliance on subsidies. Networks that survived the 1990s are constantly seeking alternative funding arrangements, including cooperative agreements with public and private organizations, grants and contracts, and station/network sponsorship arrangements.

University-based weather networks have been under considerable pressure in recent years to fund operations using grants and contracts. This type of funding arrangement is often not effective unless most of the funding is generated by long-term grants and contracts. Funding a network on short-term grants can lead to a “feast or famine” funding cycle that forces the network to adjust priorities to meet changing grant objectives or funding levels. Such a funding arrangement can lead to a loss of network focus, which can lead to reduced and/or poor-quality service to network clientele. Retention of network personnel may also prove difficult when job security and/or level of compensation depends on obtaining grants. A proper network funding balance may never be achievable, but it is best to fund essential network personnel on hard money or stable, long-term grants. Nonlabor operations can often be covered by user fees of some sort, while short-term grants and contracts represent a good funding source for operational support of existing products or product development efforts.

Lesson 5. Develop and Maintain Effective Quality Control Strategies
Quality control begins with buying quality equipment. All too often, networks purchase less-expensive equipment because of funding restrictions. However, equipment costs are relatively minor compared to long-term operating costs of equipment in the field. Sensors that fail or lose calibration quickly generate tremendous operating costs for a network. For example, the cost to perform an emergency maintenance on a sensor in the AZMET network runs from $160 to $450 per day when labor, transportation, and per diem meals and lodging are properly accounted for. A more reliable sensor that carries a higher purchase price may pay for itself in a very short time with this sort of repair cost economics.

Proper calibration is essential to data quality control, and most networks use two types of calibration procedures: standards calibration and on-site calibration. Standards calibration is generally completed at some form of calibration facility where network sensors are compared against “standard” network sensors. It is best to check sensors over the expected dynamic range of the parameter in question. Few networks possess true traceable calibration standards, but instead opt to use as “standards” high-quality sensors that are periodically returned to the manufacturer or an independent facility for calibration against traceable standards. Some networks choose to send some or all of their sensors to manufacturers for calibration, but this can be a costly process.

On-site calibration consists of comparing weather station sensors with “travel standards” over rather short periods of time. Travel standards are mounted at the site in a manner
similar to permanent station sensors, and the outputs from the standard and station sensors are compared. Station sensors are replaced if their outputs deviate markedly from those of the travel standards.

Timely maintenance is another aspect of quality control. Maintenance can be separated into two categories: technical and nontechnical. Technical maintenance involves repair and replacement of sensors and equipment, and is intimately tied to the calibration process. The only effective maintenance program for an AWSN is one based on preventive maintenance—that is, a maintenance program that rotates sensors, data loggers, and communications equipment before their performance degrades. It is essential to establish firm equipment rotation schedules based on manufacturers’ recommendations, local network experience, and the experience of other networks. A network must maintain a considerable inventory of spare equipment as well as personnel capable of repairing degraded equipment to employ an effective preventive maintenance program. Most networks find technical maintenance is best performed by internal network personnel; success of technical maintenance performed by cooperators varies.

Emergency maintenance falls under the general category of technical maintenance and is required when a sensor, data acquisition system, or power supply falters or fails. Good preventive maintenance minimizes but never eliminates emergency maintenance. It is important to designate a person or persons that are responsible for emergency maintenance. Personnel with emergency maintenance responsibilities must have the flexibility to address emergency situations on short notice and thus should not be tied to other essential network chores such as programming or database management. Often, the individual assigned to technical maintenance also performs emergency maintenance.

Nontechnical maintenance generally falls into the category of site maintenance. Station sites may require mowing, weeding, irrigation, and fence repair. Often, personnel responsible for nontechnical maintenance also clean and level sensors such as pyranometers, remove debris from rain gauge funnels, and listen for noisy bearings in rotating sensors such as anemometers. It is generally more cost effective to have local cooperators perform the nontechnical maintenance if stations are located well away from the network’s center of operations.

Running quality control checks on incoming and processed data represents another important aspect of network quality control. Most networks employ a combination of automated and manual quality control routines to assess data. Computers and attendant software perform the automated quality control routines, which include checking incoming data streams for proper format, time, and the presence of obvious bad data (e.g., sensor over range); comparing parameters against relevant physical extremes (e.g., negative rainfall or >100% relative humidity); using statistical techniques to identify extreme values; and comparing data from neighboring stations. Most automated quality control software runs unattended and either places flags on questionable data or generates summary reports for review by network personnel.

Manual quality control techniques commonly consist of plotting incoming data in various formats to look for data outliers or trends that indicate a sensor is sliding out of calibra-
tion. Today, computers can perform much of the plotting, but network personnel generally control the process and make the final determination pertaining to data quality.

**Lesson 6. Our Clientele Are Changing**
Improved communications technology and changing public priorities have combined to expand the user base for meteorological data. Most networks now disseminate data and information via the Internet, which opens the network to a worldwide audience. Networks that previously targeted their programming to state or regional areas now find their data sets being accessed and used all over the world. Changing public priorities in the area of water rights and environmental legislation have also broadened the user base for meteorological data. Scientists, consultants, and lawyers are as likely to access data from weather networks as are traditional network clientele such as agricultural producers or government personnel involved in natural resource management. This expanded clientele base translates into increased use of data collected by AWSN, which can certainly be used to justify continued operation and financial subsidies for AWSN. However, the expanded user base does come with a cost. New network clientele commonly have different vocational or educational backgrounds than traditional audiences and thus require more or different forms of assistance when using meteorological data. Networks are commonly understaffed to begin with, and this expanded need for public assistance places additional strain on personnel resources.

**Lesson 7. Products and Information Are Essential**
Collecting quality meteorological data is relatively easy because of the availability of high-quality data acquisition and computer equipment, and most AWSN do a good job of collecting data. However, the real challenge in today’s information-based society is to generate useful information or products. Many AWSN could be categorized as “data rich and information poor” because they provide all sorts of data but lack an array of products the public finds useful. Future survival of many networks will hinge on development of new weather-based products that aid clientele in the decision-making process. Some examples of products include drought assessments, frost advisories, irrigation guidelines, and pest/crop management models. Development of new products commonly requires an interdisciplinary effort; thus, network personnel must be willing to work with a wide range of scientists and policy specialists to be effective in the product development arena. A second essential aspect of product development is product awareness. It is therefore important for networks to allocate time and resources for public education and outreach activities once a new product is ready for use.

**Future Challenges**
Growing demand for meteorological data in areas such as global change research, environmental assessment, agricultural management, and public safety should bode well for the future of AWSN in the United States. However, a number of challenges serve as possible roadblocks to the survival of many existing networks that support these needs, and these challenges are discussed below.
Challenge 1. Data Redundancy
Perhaps the greatest challenge to the future of many AWSN is the perception on the part of the public and policy makers that AWSN simply generate a redundant set of meteorological data. A number of governmental agencies and universities run AWSN today. The United States government itself operates networks within a number of agencies, including NOAA, BLM, and USDA. Add to these federal networks a number of state networks ranging from flood forecast and transportation hazard systems to local agricultural and frost forecast networks, and one has the recipe for real or perceived redundancy of effort. Going forward, it will be more important than ever for AWSN to define their objectives and evaluate whether existing data sources can satisfy all or part of the network’s objectives.

Challenge 2. Growing Meteorological Databases
A second challenge for existing AWSN is the growing size of meteorological databases. These databases have tremendous value in modeling, climate assessment, and environmental impact assessment and should be maintained for future use. Many of the agricultural networks established in the 1980s provide the only long-term data sets on solar radiation, humidity, and wind over large expanses of rural America. Such databases are, however, expensive to maintain because of personnel costs, changing data storage technologies, and the need for ongoing quality control and quality assurance programs. All too often, these very necessary chores of database management are the first to be cut during lean budget periods.

Challenge 3. Future Affiliation with Agricultural Experiment Stations
Agricultural weather networks associated with land grant university agricultural experiment stations (AES) face a growing challenge as a result of changes in the funding structure and research emphasis of AES. Experiment stations are eliminating many of their service activities (e.g., soil tests; disease diagnosis), or are demanding such service activities be revenue-neutral or generate positive cash flow. Because agricultural weather networks typically receive financial subsidies from AES, the future of these networks is not particularly promising. Changes in research emphasis of AES also have worked against many AWSN. Many AES no longer hire faculty that are inclined to use near-real time weather data for applications, thus limiting the development of products for data generated by networks. It may well be that affiliation of AWSN with AES is an obsolete model. State departments of agriculture or a consortium of commodity groups may be more effective future partners for agricultural weather networks.

Challenge 4. Integration of Remote Sensing Products
Effective utilization and/or integration of remote sensing data represents another important challenge to existing AWSN. Advocates of remote sensing point to improvements in models that assess vegetation type and status, crop water use, surface energy fluxes, and precipitation and question whether ground-based meteorological measurements will be needed in the future. In reality, data from ground- and satellite-based data acquisition platforms often complement one another, and effective integration of these data sets offers opportunities for AWSN to provide localized information over broad geographic areas. Integration of these data sets may also bring much-needed funding to AWSN. Federal and
state agencies want products derived from remotely sensed data to be used, and proposals to develop products from combined satellite and ground-based data sets should attract funding.

**Challenge 5. Changing Clientele**
The clientele accessing the products of AWSN is changing. Many of the earlier North American networks were set up to support agricultural production. These networks traditionally worked with agricultural producers through standard outreach channels such as Cooperative Extension or local Natural Resource Conservation Districts. Agriculture is now undergoing rapid change in the United States and producers are now larger, better educated, and more inclined to hire professional consultants to handle critical aspects of the production cycle. These consultants demand more detail and information than many networks are prepared to deliver. In addition, consultants are less likely to use traditional outreach channels for their information, preferring instead to call network personnel directly.

Many AWSN networks also face growing demand for data and information from new clientele groups consisting of lawyers, environmental consultants, and urban water planners. These groups often demand considerable time from network personnel because they work on issues related to lawsuits, environmental compliance, or water rights. Many networks are insufficiently staffed to meet the demands of these new clientele groups, especially when network personnel get drawn into formal legal proceedings.

**Challenge 6. Improve Quality Control of Data**
Data quality control represents another interesting challenge for AWSN. Quality control is an evolutionary process that is driven by new research, network experience, new equipment (sensors, data loggers, calibration equipment), and improvements in computing power. Many networks find it difficult to keep up with the day-to-day demands of data quality control, much less find time to implement new techniques resulting from research and/or network experience. Seemingly simple decisions such as adding a new sensor can force networks into the time-consuming processing of reconfiguring and then debugging quality control software. Likewise, implementation of new data storage technology requires not just time to transfer data stored on older media, but also time to ensure that data are transferred correctly. Maintaining adequate personnel in the area of database management and data quality control will certainly be a major challenge for AWSN in the future.

**Challenge 7. Standardized Computation Procedures**
Most AWSN generate and disseminate a variety of computed variables ranging from wet bulb and dew point temperatures to growing degree days and reference evapotranspiration. In many cases, the algorithms for computing these variables were not standardized and network personnel were free to select algorithms that best fit their local needs. In recent years, however, there has been growing interest among researchers and policy analysts in developing standard computational procedures for such variables to avoid confusion and to facilitate use of both simple and complex biological models that require these computed variables as input data. Examples include irrigation scheduling models
that require reference evapotranspiration data or pest management models that require growing degree days. If computation standards are adopted, there will be growing pressure on AWSN to adopt these procedures and adjust their historical databases accordingly.

**Challenge 8. Upgrading Equipment**

Advancements in electronics and communications technology are generating a constant stream of new and potentially useful sensors, data loggers, and communications equipment for AWSN. Upgrading equipment in AWSN is by no means a trivial decision. Most equipment changes are phased in over periods as long as a year or more because of funding limitations and time constraints associated with making changes at individual weather stations. These “phase in” periods can be difficult because equipment upgrades often require changes in equipment inventory, calibration procedures, and quality control and/or communication procedures. It is important for AWSN to develop sound rationale for deciding when sensors and equipment are obsolete. Changes should not be made until a complete cost-benefit analysis has been performed and the experience of other networks implementing similar changes has been tapped. Networks should consider developing informal or formal equipment-testing consortia (e.g., regional or national committees) to evaluate new sensors and data loggers before installing new equipment in networks.

**Summary**

Automated weather station networks have become commonplace in North America, and data from these networks have found utility in applications ranging from agricultural and natural resource management to transportation safety. In this chapter, we reviewed both the lessons learned by operators of AWSN and some challenges that must be addressed by future AWSN. The future of AWSN is positive if network operators heed the lessons of the past and prepare for the challenges of the future.
The Role of Automated Weather Stations in Developing Countries

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Abstract

To introduce and understand the role that automatic weather stations (AWS) can play in developing countries, we cannot limit ourselves to evaluating the performances of a standard AWS. Instead we should put them in the context of problems experienced in developing countries.

As such, the AWS per se do not change the efficiency of an agrometeorological service if:

- they are not combined with other technologies such as remote sensing, geographical information systems, agro-informatics and agro-ecology;
- the skills of personnel are not very different from skills needed in the past to deal with computers, electronic instrumentation, satellite processing, data on a geographical basis, and choice and adaptation of crop models;
- there is not an international effort to prepare the tools, manuals, software, and learning procedures necessary to train personnel in an efficient and modern way.

Based on the above-mentioned considerations, this chapter will deal with the entire structure of the Agrometeorology (AgM) system, adapted for the characteristics of developing countries.

Introduction

When we discuss the activities in developing countries, we have to keep in mind that their financial and human resources, economic systems, traditions and behavior, and characteristics of farming (in many cases, subsistence agriculture) differ greatly from those of developed countries. We will discuss applications of AgM; the specification of AWS, depending on the desired goals; integration of data from AWS with data from other sources such as satellites or meteorological models; use of crop models; skills of the modern and innovative agrometeorologist; and the role of international cooperation in promoting and improving systems in developing countries. This chapter provides a brief discussion of the role of automated weather stations in developing countries. For additional information, please consult the references ("Further Reading") at the end of the chapter.

The Applications of AgM in Developing Countries (DC)

The main goals of AgM in DC are to improve the stability of production from year to year and increase national agricultural production. In large part, the main product of agricul-
ture in DC is food for farmers themselves, even though the growth of towns in the last few decades has led to a demand for food for nonrural populations. The principal aims of AgM can be summarized as follows.

- Early Warning Systems: The ability to forecast lack of production would allow governments to determine how much food will be available and whether international cooperation through humanitarian aid would be needed to reduce the impact of unfavorable years.
- Technical assistance during the agricultural season, monitoring meteorological parameters and comparing this data with previous years and with modeled conditions. This enables timely advisories to farmers on how best to take advantage of favorable conditions or minimize adverse effects of unfavorable conditions by choosing the best time to seed, strategies that save water, weeding at the right time, or effective treatments of pests and disease.
- Improving production systems: In many of the poorest countries the improvement of production through the application of technological inputs such as fertilizers and machines is very difficult for financial reasons. Using simple techniques to take the greatest advantage of natural and human resources is the only way to improve and sustain production. Because climate is one of the natural driving forces, agroclimatic analysis and advice become crucial to improve the situation.

The Role of AWS in the Context of New Technologies
Because the new AWS can play a different role from the traditional stations that are still widespread in DC, their output should be combined with various other information to develop an integrated system, so that satellite processing, geographical information systems (GIS), climatic databases, and numerical weather forecasts (NWF) become part of a modern AgM integrated system (AgMIS).

The Agrometeorologist of 2000 in DC
As in the services of developed countries, there is the possibility that various persons may specialize in each field, with a high degree of interaction in the whole AgM system. But for DC, in most cases, only one or a few people are in charge of agrometeorology. Therefore, although this division of work is in theory desirable, it is not possible. The consequence is that agrometeorologists in DC should have at least a minimal familiarity with different subjects. Choice of the type of station, calibration and maintenance of the sensors, data transmission, data archiving and processing, spatial relations, combination with other types of data, choice of crop models, and information processing are operations that in most cases are done by the same person.

The Role of WMO and the International Scientific Community
Although new technologies such as AWS significantly increase the possibility of applications in DC, the new approach can be most effective only if the World Meteorological Organization, together with the international scientific and technical community, promotes a series of actions to institute these new technologies.
Among these actions, we will cite some specific activities for enhancing the capability of the countries to replace their old networks with new ones. Other more general activities will ensure that people in charge of the AgM services get the maximum advantage from integrated AgM systems.

An important action that should be taken is the identification of a new approach to define the characteristics of networks, with specific needs—for example, a network that requires measurements of rainfall alone. In that case, we need to define the standard sensors and the station components, including the transmission system.

We will discuss the methodology to compute the economic benefit of an AgM service to demonstrate to the policy makers how a good AgM service would improve national agriculture.

Last but not least, all activities concerning training should be upgraded, not only in workshops but also in the identification of the expertise of the modern agrometeorologist, the preparation of operational software, and the preparation of learning software and technical manuals.

**Roving Seminars on AWS in DC Sponsored by WMO**

Cooperation between WMO and the CNR–IATA (National Research Council—Institute of Agrometeorology and Environmental Analysis for Agriculture) has resulted in three roving seminars, held in Bahrain from October 24 to November 4, 1998; in Morocco from June 28 to July 8, 1999; and in Iran from November 27 to December 8, 1999. In all, 78 representatives from 22 countries attended these seminars (Table 1).

**Table 1. Countries represented at Roving Seminars on AWS.**

<table>
<thead>
<tr>
<th>COUNTRIES REPRESENTED AT THE ROVING SEMINARS ON AWS</th>
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<tr>
<td><strong>Bahrain, 1998</strong></td>
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<td>• United Arab Emirates</td>
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<td>• Bahrain</td>
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<td>• Oman</td>
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<td>• Kuwait</td>
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<td><strong>Morocco, 1999</strong></td>
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<td>• Mali</td>
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<td>• Burkina Faso</td>
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<td>• Ivory Coast</td>
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<td>• Niger</td>
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<td>• Senegal</td>
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<td>• Ghana</td>
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<td>• Guinea Conakry</td>
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<td>• Cape Verde</td>
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<tr>
<td><strong>Iran, 1999</strong></td>
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<tr>
<td>Institutions:</td>
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<tr>
<td>• IRIMO (Iranian Met. Organization)</td>
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<tr>
<td>• Agricultural University</td>
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<tr>
<td>• Health and Environmental Service</td>
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<tr>
<td>• Radiological Monitoring Service</td>
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</table>
The CNR–IATA Institute, founded in 1981, has been recognized as an RMTC (Regional Meteorological Training Centre) by the World Meteorological Organization in Geneva for REGION VI (Europe) and is able to issue specialization certificates with international value in the field of meteorology, climatology, and remote sensing applied to environment and agriculture. The Institute has experience in cooperative projects since 1985, and at this time it is engaged in three projects in Africa and two in the Middle East.

The first meeting, in Bahrain, saw the participation of representatives of the Arabian Gulf countries: Bahrain, Oman, Qatar, United Arab Emirates, Saudi Arabia, and Kuwait.

At the second meeting, held in Morocco, the representatives of sixteen countries of north-western Africa were present: Algeria, Benin, Burkina Faso, Cape Verde, Ivory Coast, Guinea Conakry, Mali, Mauritania, Morocco, Niger, Senegal, Chad, Togo, Tunisia. The third meeting, held in Tehran, was attended by Iranian personnel belonging to different local institutions.

The personnel of CNR–IATA of Florence directed these two-week seminars offering both theoretical and practical presentations. A complete instrumentation set was shipped to each seminar's location and set up to demonstrate practical activities. The equipment included electronic sensors, programmable data loggers, and a complete weather station with satellite data transmission. A technical manual has been issued to support all these activities—Manual on Instrumentation and Operations for Automatic Weather Stations for Agrometeorological Applications, published in 1998 (Figure 1). The manual’s struc-

![World Meteorological Organization](image_url)

C.N.R. - I.A.T.A.
Institute of Agrometeorology and Environmental Analysis for Agriculture - National Research Council
W.M.O. Regional Meteorological Training Center - Region VI

Manual on Instrumentation and Operations for Automatic Weather Stations for Agrometeorological Application

P. Battista, G. Maracchi, F. Sabatini, M.V.K. Sivakumar, A. Zaldei

Figure 1. Cover of WMO technical manual.
ture follows the logical steps from the choice of sensors and data logger to field installation and subsequent maintenance. Details about calibration principles and practical examples of sensors’ calibration techniques are also included.

The manual has been developed in collaboration with personnel of the Applied Meteorology Foundation and the Center for the Application of Computer Science in Agriculture. Special efforts have been made to give a complete and simple description of current methodologies to perform correct meteorological observations. The technical manual has the following organization:

1. Sensors
2. Data Acquisition Systems
3. State of the Art and Available Instrumentation
4. Utilization and Maintenance of Automatic Agrometeorological Stations
5. Instrumentation Power Supply and Protection
6. Sensor Calibration
7. Data Analysis and Archiving
8. Examples of Installations for Specific Purposes
9. Appendices

Each chapter has been subdivided. Chapter 1, for example, is organized as follows:

1. SENSORS
   1.1. Temperature
       1.1.1. Thermocouples
       1.1.2. Thermistors
       1.1.3. Thermostructures
       1.1.4. Integrated sensors
       1.1.5. Linearized thermistors
   1.2. Air Humidity
       1.2.1. Hygrometric sensors
       1.2.2. Psychrometric sensors
       1.2.3. Dew-point sensors
   1.3. Soil Humidity
       1.3.1. Neutron probe
       1.3.2. Bouyoucos probes
       1.3.3. Tensiometers
       1.3.4. Time Domain Reflectometry (TDR)
   1.4. Air Pressure
       1.4.1. Capacity sensors
       1.4.2. Inductivity sensors
       1.4.3. Piezoelectric sensors
       1.4.4. Potentiometric sensors
       1.4.5. Semiconductor sensors
   1.5. Solar Radiation
       1.5.1. Thermopile
       1.5.2. Photocell
1.6. Wind Speed
   1.6.1. Cup anemometer
   1.6.2. Hot wire anemometer
   1.6.3. Ultrasonic anemometer
   1.6.4. Doppler anemometer

1.7. Wind direction

1.8. Rainfall
   1.8.1. Pluviometer
   1.8.2. Meteorological radar
   1.8.3. Rain drop energy sensor (impactometer)

1.9. Evaporation
   1.9.1. Evaporimeters
   1.9.2. Lysimeters

1.10. Leaf wetness

1.11. Soil heat flux

The first versions have been published in English and French. The Spanish version will soon be available. WMO provided a copy of the manual for each participant. At the beginning of the meetings, an introductory questionnaire was distributed to determine the background and expectations of the countries' representatives relating to modern equipment (Figure 2). At the end of the seminar, the participants were asked to fill out an evaluation form addressed to the WMO, providing comments and suggestions for adjusting or improving the structure of these courses. For the most part, the people who attended the meetings are in charge of their respective national weather services (which often maintain a division of agrometeorology).

Figure 2. Participants’ backgrounds.
Participants with different backgrounds were also present. Some of them work for civil aviation services, university departments, or private companies.

The first impression from all the seminars was that the basic meteorological or agrometeorological knowledge was good. But although the operations relating to classic instrumentation were clearly understood by most of the audience, the operational principles of electronic sensors, in some cases, were not known or were misinterpreted.

If we consider the number of countries represented at the seminars, we obtain a huge “sample” to understand which subjects are considered more important by the participants. The graph in Figure 3 indicates the number and the areal extent of each state.

The information collected shows that the installation of an AWS network, or the improvement of an existing one, is the application that participants would most like to develop. In Figure 4, the percentages of the results are shown. It should be noted that some important aspects such as calibration and training are not considered primary subjects to be developed.

**Conclusions**

In many areas in the last 20 years, we have observed the proliferation of automatic weather stations (AWS) that offer the possibility of collecting a large amount of unattended data. This process has been expedited by decreasing costs of sensors and data loggers. Despite the favorable trend, these stations still do not cover many regions. This problem can be traced to different origins: financial, organizational, or professional. The main factor that

![Figure 3. Number and area of countries.](image-url)
still limits AWS in many areas is the cost. It can be economical for some countries but not accessible for others.

The second reason is related to a certain delay by the organizations that manage the observation network: some countries already have a high degree of economic autonomy but they still base their measurements on classical instruments (mechanical or direct reading devices). The third aspect is associated with a lack of training of specialized personnel necessary to maintain modern equipment.

Based on the discussion and from the responses collected on the questionnaires, insufficient deployment of AWS is the most common complaint. Moreover, the AWS networks in use (and sometimes this refers to only one AWS, deployed in the main airport) suffer from frequent lack of data because of a limited number of technicians and poor organization. Obstacles to equipment management (such as maintenance inspections, spare parts acquisition, or calibrations scheduling) also exist.

To meet the needs of DCs, the AWS should furnish unattended data from remote sites with a satellite telemetry option, because normally those areas are not covered by other telecommunications systems. Because of the specificity of the applications, it could be useful to install simple stations that do not completely displace classic observation methods.

The most valuable characteristics of AWS in DC are their low cost, simplicity of use, and reliability. Of course this could be seen as the ideal situation for any application, but these features have to be highlighted when we work in such environments. Simple installation and simple inspection operations with modular equipment are preferable. Although this may limit the flexibility of AWS, in this case a simple sensor configuration with few operations is preferable.
Satellite transmission is a good solution despite its costliness. Many African countries are using free MeteoSat satellites for remote data transmission, but because of limited numbers of time slots and drift of local AWS clocks, the communications sometimes fail to stay in the assigned time slot. Other new satellite systems are now available. In our institute we have tried the LEO (low earth orbiting) satellite network, in order to set a fast installation system with a transmission cost comparable to other telemetry options such as phone, cell phone, or radio.

It is not only financial aspects that limit the use of AWS. Often, personnel trained to use modern equipment are not available. For this reason, WMO has organized (and will organize) a cycle of roving seminars on AWS to give an updated overview of the capabilities of modern systems.

Acknowledgments
The authors wish to thank all the staff of CNR–IATA (National Research Council–Institute of Agrometeorology and Environmental Analysis for Agriculture), AMF (Applied Meteorology Foundation), and CeSIA (Center for Computer Science in Agriculture–Georgofili Academy) for the support provided in this activity.

Further Reading
Communication with AWS
Cellular Communications for Automated Weather Stations

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Abstract

The increased placement of automated weather stations in remote locations and the development of cellular communications in developed and developing countries has resulted in the provision of cellular communications as a viable option for the telemetry of automated weather station (AWS) measurements. This chapter provides detailed information on the disadvantages and advantages of this method of telemetry, and details on the characteristics and installation considerations for the components required for cellular communications with automated weather stations. Examples of operational considerations are drawn from our experience with the Purdue Automated Weather Station Network (PAAWS).

Principles of Operation

Cellular communications is fundamentally a duplex radio frequency radio system, providing two-way communications without having to alternate between receiving and sending information between the station and the data logger. There are two cellular communications services: analog and digital.

Analog cellular service is called AMPS (Advanced Mobile Phone System), which operates in a bandwidth of 824–894 MHz. In the United States, there are two carriers (A and B) per metropolitan service area (MSA) or rural service area (RSA). AMPS service uses two frequencies (send and receive), each with a bandwidth of 30 KHz separated by 45 MHz within the A or B wavebands (Figure 1).

<table>
<thead>
<tr>
<th>800 MHz</th>
<th>856 MHz</th>
<th>926 MHz</th>
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<tr>
<td>(824 MHz)</td>
<td>(894 MHz)</td>
<td></td>
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</tbody>
</table>

Send <= 45 MHz => Receive  Send <= 45 MHz => Receive

Figure 1. Analog communications wavebands.

Each carrier can have up to 416 duplex voice channels within their assigned band. Analog cellular service breaks the land area into cells of approximately 10 sq. mi., with each cell using 1/7th of the available 416 channels. This results in a maximum of 59 channels available for any given time and cell. Data transfer rates are 1200 to 2400 bps.

Digital cellular service characteristics vary across the world. All digital service has a compressed voice signal, allowing 3–10 duplex calls per analog call. Since each cell in digital service uses 59 analog channels, the digital service can have 177–570 digital channels (calls) at any given time. Three digital protocols exist: GSM (Global System for
Mobile communications), TDMA (Time Division Multiple Access), and CDMA (Code Division Multiple Access). However, of these three protocols, only GSM and CDMA protocols are currently being developed.

GSM digital service operates in the digital frequency band around 1.8 GHz and is prevalent in Europe and Asia. GSM uses smaller cells than analog service and has lower power needs than analog service because the signal does not have to carry as far to the tower. The use of different cell sizes than analog also means that those places with analog service must build new towers for the digital service. Transmission rates are voice at 13Kbps and data at 9600 bps.

CDMA digital service can operate in either the digital or analog bandwidth. For the United States, the digital bandwidth is 1.85GHz–1.99 GHz. This service uses existing analog cells. It has 20 times the call capacity of analog service per cell because the information being transmitted is compressed. The digital transceiver powers down in accordance to distance to tower, resulting in lower power needs than analog service. Transmission rates are voice at 13Kbps and data at 9600 bps. CDMA digital service has been developed and marketed in the United States by Qualcomm, Inc.

Digital cellular communications has distinct advantages over analog service when considering data transfer rates, number of simultaneous calls possible at a single tower, and clarity of the communications link. However, since analog service has been extensively developed in the United States and analog transceivers are used in existing AWS cellular communications configurations, it is still believed to be the only cellular communications protocol used in AWS networks in the United States.

The adoption of analog cellular communications for automated weather stations must take into consideration some advantages and disadvantages. Advantages of (analog) cellular communications include: maximum flexibility in locating stations, minimal risk from mechanical damage due to farm machinery, minimal risk of lightning strike damage, minimized costs of installation at locations distant from existing phone lines, and minimized costs of moving stations due to changing farm/researcher needs. The disadvantages of cellular communications include: the service being limited to regions with cell towers, relatively high power needs, relatively low data transmission rates, and rapidly changing technology.

**AWS Installation Considerations**

The hardware needed to have cellular communications at an automated weather station consist of an antenna, transceiver, cellular to land-line protocol converter, and modem (Figure 2). To evaluate whether cellular communications is a possible solution to automated weather station communications, determine (1) if the right kind of cellular service (analog or digital) is available in the area of the AWS site, (2) what waveband the cellular provider uses, (3) whether there is a cell tower in line of sight and within 16 km of the AWS site, and (4) whether you have sufficient power at the site to meet the needs of the communications equipment.
To determine the availability of service within the requisite 16 km, you must know the exact location of your AWS and the exact location of the nearest cellular service towers. In the United States, there is a Federal Communications Commission registry of all towers (location, height of antenna, owner, etc.) on the WWW Wireless Telecommunications Bureau web site (http://www.fcc.gov/wwb/) under WTB database files. The distance to the nearest tower should be within 16 km for telemetry use. Nearby antennas, radar, and other RF sources can cause problems with the communications by introducing substantial noise to the signal.

**Cellular Service Provider**

Once you have decided to go with cellular communications, understand that it will probably take time to get the service provider to understand your service request. Since they are oriented toward mobile voice communications needs, they have a hard time understanding a non-mobile telemetry need. A visit by a service representative from the cellular provider to your AWS can be a big help in their understanding of your need. Be aware that the cellular communications services are rapidly changing from analog to digital in high-population areas to maximize users/cell and that gaps in service exist. When service is established, be sure to get detailed billings and watch for roaming charges where your station is accidentally being picked up by distant towers. Cellular service engineers are constantly adjusting cellular tower transmitters to optimize performance—they assume that the average user will not become irate because as he or she loses the signal from the
tower they are working on, they soon pick up the next tower down the road. Since they are not used to considering non-mobile users, you must be monitoring problems as they develop, because they may well be due to actions the provider has taken to optimize performance for the standard user. The best way to limit problems is to cultivate a good AWS technician to cellular service provider technician relationship so that your communications problems can be quickly isolated and solved.

Antennas

Once the service provider has agreed to give you telemetry service, be sure that you buy the right antenna, as the analog A and B bands (in the United States) use different antennas. If the wrong antenna is used, you may still get occasional reception, but you will not have consistent, reliable communications. When choosing an antenna, choose one that has as low a gain as possible to minimize the amplification of noise in the signal. Two types of antennas are used in cellular communications: the omni-directional antenna and the directional YAGI antenna. An omni-directional antenna typically has a less-than-one dB gain that is not direction dependent. A map of the relative gain of the omni-directional antenna perpendicular to the earth is illustrated in Figure 3. The greatest gain is found for RF signals along the plane perpendicular to the axis of the antenna and typically at the earth’s horizon for the vertically mounted antenna. In the earth parallel plane, the gain at any elevation from the horizon would look like a donut, with significantly decreased gain when the antenna is greater than 30° off the horizon. These antennas are designed for vehicle use, with the vehicle as the ground plane for the antenna. A ground plane must be installed for proper function in AWS communications, but these are often omitted in shipping. You will probably be able to communicate with the AWS erratically even if you do not have a ground plane installed, but adding the ground plane will stabilize the reliability of communications. The directional YAGI antenna typically has a 3 to 5 dB gain (enhancement of reception and amplification of transmission) in a specific direction. The YAGI is a polarized antenna, so the change in antenna gain when changing your angle horizontally to the antenna (side to side) differs from that when you change your angle to the antenna in the vertical (up and down) direction. There is a broader range in orientations, with higher gain in the plane of the elements (left panel, Figure 4) than in the plane perpendicular to the elements (right panel, Figure 4). Typically, for AWS use, the YAGI is mounted with the elements vertical, so the inclination angle between the cell tower and the antenna has the least effect on performance. In the earth-parallel plane, the antenna is highly selective, with high gain in a narrow range of angles from the axis of the antenna spine (right panel, Figure 4). Since it is highly directional in the earth parallel plane, the antenna needs to be carefully pointed (within 10 degrees or so) toward the cell tower to be used for communications. One cautionary note: keep at least ½ wavelength away from an active (powered) antenna when making a bearing reading by compass, or the compass will be affected by the magnetic field of the antenna.

All antennas should be mounted as high as possible because the optimal amplification and emission of the antenna is along the axis of the YAGI and perpendicular to the vertical whip of the omni-directional antenna (Figures 3, 4). It is preferable to have the nearest cellular tower in line of sight or at least not obstructed by large structures at a distance or metal structures nearby. Metal objects that are parallel to the elements of a YAGI antenna will be most effective at degrading performance. We had problems with
Figure 3. Directional sensitivity of an omni-directional antenna. The profile of the antenna is overlain on a plot of the relative gain of the antenna in the vertical plane. dB is a logarithmic measure of gain or amplification of the signal, with negative values indicating less gain than that of the maximum direction at the horizon (modified from Antenna Sourcebook [Anonymous, 1999]).

Figure 4. Directional sensitivity of a YAGI antenna. The YAGI antenna is superimposed on the pattern of relative gain by the typical YAGI antenna. A greater distance between the center and the envelope denoted by the solid line indicates greater gain of the antenna in that specific direction. The left panel indicates the pattern of antenna gain parallel to the earth’s surface and perpendicular to the antenna’s plane. The right panel indicates the pattern of antenna gain perpendicular to the earth’s surface and parallel to the plane of the antenna (modified from Antenna Sourcebook [Anonymous, 1999]).
communications when a YAGI antenna was pointed to a tower across a nearby vineyard because the vines were supported by an array of metal wires. All antennas should be mounted on nonconducting booms. YAGI antennas need to be mounted such that the AWS mast or tower does not lie between the antenna and the cell tower. Be aware that the communications performance may change as equipment on the AWS changes due to RF reflections.

When dressing the cables from the antenna to the data logger, be sure to use cable ties to secure the feedline RF cable (the cable connected to the antenna) and be sure that the cable is the right length to match the impedance of the antenna. The positioning of the cable also can influence the reliability of the communications. For a YAGI antenna, the feedline RF cable should come out behind and below the antenna in a loop before descending down the AWS mast or tower. For the omni-directional antenna, the feedline should come down smoothly from the antenna. Avoid making loops with the RF cable, and avoid sharp turns as the cable is dressed down the tower or mast and into the data logger and telemetry enclosure.

**Transceiver**

Each transceiver must be programmed with the telephone number and various provider codes. The programming and voice communications can be made using a plug-in handset. However, be aware that the matching of handset to transceiver is highly specific. Each transceiver has electronic serial numbers (ESN) that are unique to the transceiver and must be provided to the service provider so that the physical device can be associated with the phone number. Since this association is necessary to complete a connection, swapping transceivers at an AWS will take time.

Some difficulties in communications result from the overloading of the channels available for communications at the tower. The cellular tower equipment “knows” your transceiver is there at all times it is in quiescent or active mode and can selectively accept your call over other calls. In quiescent mode, transceivers “ping” the tower regularly to indicate availability for call reception. Transceivers also have various priority codes for the towers to acknowledge the transceiver, and you may be able to get the service provider to shift the priority of your “call” relative to other calls. The technician needs to visit your AWS site and make the changes himself.

In PAAWS as well as other AWS networks, the transceiver is a 3W analog “bag phone” of Motorola. Since a handset can be attached to the transceiver, it is also used by the technician on-site for calls to the office and company representatives. Therefore we mounted the transceiver in the enclosure so that it is readily accessible for testing, programming, and in-field voice use. The power needs of the transceiver are relatively large: the transceiver uses approximately 2.15 A when active and 0.38 A when waiting for a call (PAAWS network). Because of the high power need of the transceiver, one must limit the hours in which the cell phone is available for receiving or transmitting. With a 9-hour daytime access and a 20W solar panel, our 38 AhR battery dropped by 0.3V per day under full summer sun (latitude approximately 40°). With our current 40W solar panels and a 12-hour access window, the battery drops 0.1V during heavy overcast days and fully re-
charges during most days near the winter solstice. During the summer we have a 24-hour access window that results in a 0.2V drop in the battery under heavy overcast days, and it fully recharges on most days.

**Modems**

Although the commonly used basic settings on the modem (baud rate, number of stop bits, number of data bits, and parity) set for land-line use are also necessary for cellular communications, additional settings related to delay and wait times (registers S7, S9, S10, S19, S25, S38) also need to be set for proper cellular communications. For example, noisy signals may be dropped by the modem because of the delay between data packets, so extending the time interval in register S10 will increase communications reliability. Baud rates need to *match* between calling modem and receiving modem (cellular connections are typically at 1200 to 2400 Baud), as the time it takes to automatically establish the proper baud rate is often too long for the cellular transceiver.

**Purdue Automated Agricultural Weather Station (PAAWS) Network**

The PAAWS network is a 9-station network of AWS located at each of the agricultural experimental centers around the state of Indiana. Communication with each AWS is solely by cellular telephone service. The network was designed to support both operational production and university research activities. Variables measured by the AWS include air temperature, wind speed, wind direction, precipitation, global solar radiation, and soil temperatures at 4 inches under grass and bare ground. Operational use relies on a synthesized voice that provides the caller with current air temperature, current wind speed and direction (reporting the eight ordinal directions: “northeast” instead of “45 degrees”), and highest wind gust in the past half hour. The primary means for researchers to gain access to the data is through the Internet (http://shadow.agry.purdue.edu/sc.zen-geog.html). The present operational users consist of local fire departments for wind information during fires and farm managers for temperature information related to freeze conditions and wind information for decision making on herbicide and pesticide spraying activities. The web-accessible database is updated daily near the time of minimum air temperature. The web database produces half-hour, hourly, or daily summaries in formats using either English or metric units for any period of record and any subset of variables.

**Overall Communications Performance**

Once established, the overall performance of the communications system can and will be occasionally affected by noise. Greater noise in the connection results in a diminished signal to noise ratio, degrading the quality of the information being passed through the communications system. While cellular communications appear to be only RF, a land line (hardwire telephone line) is commonly involved in completing a call. For our daily PAAWS data download, the communications path of the data includes: (1) RF signal from the AWS to the cellular tower, (2) transfer of the RF signal off the tower to a land line “leased” by the cellular provider from the land line telephone service provider in the area of the tower, (3) a second transfer of the signal to land lines owned by the same company that provides the cellular service, and finally (4) the receipt of the signal by our computer modem. Some communications problems may lie with the land line service. Listen to the
connection through your phone to detect signal strength and the amount of noise in the signal. Communications problems in the PAAWS network have included land-line switching equipment problems and cellular tower outages and changes. Hardware problems associated solely with the AWS hardware have been limited to RJ wire connectors, wire routing, and the cellular interface.

Also, expect some variability in performance influenced by weather conditions (atmospheric stability affects RF transmission), time of day (saturation of channels available on a given tower antenna may be related to traffic), and the seasonal foliage amount. In PAAWS, the time of the automated dialup of stations varies with AWS location to avoid times of local peak use.

**Future Directions**

Populated areas of the United States are experiencing a rapid change from analog to digital cellular communications. Cell towers are being converted from analog to digital service, leaving only a small fraction of the tower communications at analog service wavelengths. This is resulting in increased loading for the fewer analog channels available on a given tower, and therefore a reduction in the accessibility of available analog service for AWS telemetry use. We do not know of any digital transceivers adapted for AWS telemetry in the United States as of 2000.

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Use of Cell Phones for Data Retrieval in Arizona

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Abstract
The Arizona Meteorological Network has installed analog cellular telephones (CT) to facilitate data retrieval from automated weather stations. Cellular telephones proved to be a more reliable telecommunications link for weather stations located in remote rural areas with poor-quality, land-based telephone lines (LTL). Use of CT for data collection in lieu of LTL results in higher numbers of failed calls and required retransmissions of data, but these problems rarely limit data collection. Cellular telephones are generally less expensive to install and much less expensive to operate than LTL. Lower monthly operating costs of CT in Arizona can pay for the CT equipment package in less than one year, and the CT package and upgraded power supply in two years. Power management is the major impediment to using cellular phones for data retrieval. Power supplies must be properly matched to meet the combined power requirements of the CT and weather station. Lower power requirements can be achieved by supplying power to the phone only during periods when station access is required. The major negative factor associated with using CT in Arizona has been poor-quality technical and operational assistance provided by local service providers and the CT manufacturer.

Introduction
A number of automated weather station networks have utilized land-based telephone lines (LTL) as the telecommunication link between remote stations and the network data processing center (e.g., Hubbard et al., 1983; Snyder et al., 1985; Brown, 1987). Although LTL have proved effective as a telecommunications strategy for many networks, a number of problems can arise when networks are totally reliant on LTL for telecommunications, including (1) lack of service in many remote areas; (2) poor-quality service; (3) limited flexibility when siting weather station equipment; and (4) high installation and monthly service charges. Cellular telephone (CT) service is now readily available in much of the United States and thus offers networks an alternative to LTL for telecommunications. The Arizona Meteorological Network (AZMET), a near-real time weather network located in southern Arizona, began using analog CT in 1994 at remote weather station sites where LTL service was nonexistent or of poor quality. The initial AZMET experience with CT was very positive, and the network now uses CT for telecommunications at 70% of its weather station sites. This chapter presents a summary of AZMET’s experience with using analog CT for data retrieval.

Materials and Methods
The Arizona Meteorological Network was established in 1986 to provide weather data and information in near-real time to producers of agricultural and horticultural crops in Arizona. Since the mid 1990s, AZMET has operated a network of 23–26 automated weather stations. Each weather station consists of a data logger (Model 21X, CR10, or CR10X,
Campbell Scientific, Inc., Logan, Utah), power supply, tripod tower, and attendant sensors required to monitor air temperature, relative humidity, solar radiation, wind speed, wind direction, precipitation, and soil temperature. The power supply includes a 33 amp-h, 12 V lead acid battery (Guardian Model DG12-32, Douglas Battery Corp., Winston-Salem, North Carolina) and charging system consisting of a 10 W solar panel (Model MSX10, BP Solarex, Linthicum, Maryland) and a 12 V voltage regulator (Model PBRS12-8D, Sun Amp Corp., Scottsdale, Arizona; or Model CH12R, Campbell Scientific, Inc.). Station data loggers are programmed to monitor sensor output every 10 s and summarize relevant meteorological means, extremes, and totals on an hourly and daily basis. A personal computer in the AZMET data processing center (DPC) running the PC208 telecommunications software (Campbell Scientific Inc.) retrieves data from the data logger once each day between 0000 h and 0100 h. Station data files range in size from 2 to 4 Kbytes and data transfer requires ~1 min at modem speeds of 300–1200 bits s⁻¹.

The CT package located at each weather station consists of an analog CT with 3 W transceiver (Model SEIII Attache Phone, Motorola, Inc., Schaumburg, Illinois), dial-tone interface (Cellular Connection Model S1936, Motorola, Inc.), modem (Model DC112 or COM200, Campbell Scientific Inc.), and either an omnidirectional magnetic mount or Yagi directional antenna. Antennae are mounted near the top of the station tower ~3 m above the surface. Phone use was evaluated during two periods, referred to as Phase 1 and Phase 2. Phase 1 lasted from 1994 to 1999 and involved leaving the CT fully powered for 24 h d⁻¹. Phase 2 covers the period from 1999 to present, when a power management control circuit was added to the CT package to reduce power consumption. The circuit is connected to data logger control ports and activates a relay that switches power to the CT during the following time periods each day: 0700–1000 h, 1430–1530 h, and 2345–0130 h.

Results and Discussion

Power Requirements

The high power requirement of the CT was the major problem encountered when switching station telecommunications from LTL to CT service. Cellular telephones function in two basic operating modes: standby mode, when the phone is awaiting a call; and active mode, when the phone is handling a call. Phones in standby mode draw ~115 mA of current, which translates to a power requirement of 1.4 W. Phones in the active mode draw ~1.2 A—a power consumption of ~14 W. Total power requirement at the weather station consists of the power requirements for the CT plus that of the data logger and sensors (~0.4 W) and thus ranges from ~1.8 W when the CT is in standby mode to ~14.4 W when the CT is active. The single 1 min call required to retrieve the previous 24 h of data from an AZMET station increases daily power consumption ~1% above the station power requirement when the CT is in standby mode. It is important to note that longer data retrieval periods or more frequent data retrieval does significantly affect total power consumption. For example, an hourly retrieval frequency with calls lasting 1 min would increase power consumption by ~12% to 2.0 W.
Matching the power supply to power consumption is the important issue when using CT at weather stations. The 10 W solar panel serves as the source of energy for the AZMET power supply. Panel energy output varies with sky conditions, temperature, and time of year and ranges from 1.7–2.9 W-h in summer to 0.4–1.9 W-h in winter when averaged over a 24 h basis. The lower and upper ranges of available energy occur during cloudy and clear days, respectively. Cloudy days are rather rare in Arizona, so available energy generally runs near the upper end of the ranges listed above. During Phase 1, when CT were left on 24 h d⁻¹, AZMET experienced few problems with the existing power supply during summer because available energy generally exceeded the station energy requirement of ~1.8 W-h. In winter, however, power provided by the solar panel was insufficient to offset station power consumption during cloudy weather and/or the shorter days of December and January, resulting in a gradual discharge of station batteries. Battery replacement was required at several stations during winters when cloudiness was above normal.

Use of the power management control circuit during Phase 2 nearly eliminated the battery discharge problems during the winter of 1999/2000. The circuit relay that regulates power to the CT adds 0.35 W to the total station power requirement when the phone is supplied with power. However, because the phone is operational only 5.75 h d⁻¹, the daily energy requirement, when averaged over 24 h, drops to ~0.8 W-h, which is well below the available energy (>1.5 W-h) during most winter days. It is important to note that the winter of 1999/2000 was a clear and mild winter in Arizona. Evaluation of the power management control circuit will continue in subsequent years to ensure that available energy from the power supply is adequate during winters with less sunny weather.

Quality of Telecommunications
Cellular telephones proved to be a viable alternative to LTL for data retrieval, and AZMET now uses CT on 16 of the network’s 23 stations. Use of CT at station sites with poor LTL service improved data collection immeasurably. Figure 1 provides a comparison of communication problems experienced at weather stations using LTL and CT for data retrieval during the final six months of 1999. Use of CT led to a greater number of retransmission requests and failed calls. Retransmission requests refer to situations where error checking routines within the communications software detect a problem with the received data and request that the data be sent again. The higher number of retransmission requests associated with CT is related to bursts of static or noise that appear with some frequency with analog cellular service. These noise events are usually brief and rarely result in truncated calls or garbled/lost data. Data files obtained during calls with retransmission requests are typically complete and thus can be processed in the same manner as calls where no retransmission requests are recorded.

“Failed calls” refers to situations where the DPC was unable to contact the weather station and download data. The higher number of failed calls associated with CT would seemingly be a very negative factor for a near-real time weather network. However, AZMET employs a recall routine that attempts to call all weather stations (both CT and LTL stations) two additional times if the primary data retrieval call fails. Backup calls are often successful, which means data are still received and processed on many nights when failed calls are registered. The reason for the relatively high number of failed calls with
Figure 1. Number of failed data retrieval calls and required retransmissions of data for automated weather stations using cellular telephones (CP) and land-based telephone lines (LTL) for telecommunications during the six-month period ending December 31, 1999.

CT is not fully understood; however, we have observed a tendency for calls to fail at multiple stations within a general geographic area and believe these failures relate to actions taken by the service providers (e.g., system maintenance). Failed calls can occur with some regularity when the CT system is operating near full capacity; however, it is unlikely the system would be busy during the period 0000–0100 h, when AZMET retrieves data from stations.

Cost
Cellular phones are generally less expensive to install than LTL. Local LTL companies commonly charge $300–$1000 to install phone lines in or adjacent to agricultural fields in Arizona. Differences in trenching and cable requirements and varying connection and service establishment fees account for the wide variation in costs. Establishment of CT service requires the payment of a setup fee, which runs ~$35, and purchase of CT equipment consisting of phone, interface, and antenna for $300–$400. Timeliness of installation is also another advantage of CT. Most CT service providers can activate phones the same day they are purchased, which allows for same-day installation. Installation of a LTL can require a wait of several weeks or months.

Cellular phones are far less expensive to operate than LTL in Arizona (Figure 2). Phone companies that provide LTL service impose a monthly service charge of $50–$75 for phones located at AZMET weather stations. Long-distance charges add ~$4 per month to the cost of data retrieval, bringing total monthly operating costs to $54–$79 per station when using LTL. Cellular phones are less expensive to operate because AZMET benefits from favorable government rates for monthly service that range from $9 to $15 per station. Combined monthly cellular and long-distance charges run less than $10 per station, which brings the total cost of using CT for station telecommunications to $19 to $25 per
Figure 2. Typical monthly operating cost of using cellular telephones (CP) and land-based telephone lines (LTL) for data retrieval from automated weather stations in Arizona.

month. The monthly cost advantage of CT over LTL is ~$35, which pays for the cost of the CT package in less than one year and the CT package and power supply in less than two years.

Durability of cellular equipment is another factor that should be considered when assessing the cost effectiveness of using CT. The CT comes with a three-year warranty, and we have found the CT and related peripherals to be very durable. Only one CT has failed since 1994, and this phone was returned to service after the provider made a simple, cost-free frequency adjustment to the transceiver.

**Siting Flexibility**

Flexibility in siting weather stations is an important benefit of using CT for data retrieval. Sites for stations connected to LTL are frequently limited by the location and capacity of the local telephone cable, and service providers are reluctant to install cables in fields where agricultural machinery is used on a regular basis. Use of CT adds a great degree of portability to weather stations. Stations can be placed nearly anywhere cellular service is available, which can be very important in situations where the quality of the upwind fetch is important (e.g., estimating reference evapotranspiration).

**Technical and Operational Support**

Weak technical and operational support for CT was the major negative factor associated with using CT for data retrieval at weather stations. Local service providers focus their support efforts on businesses and individuals that use CT for audio communications while at work or in transit. Use of CT for data collection is apparently not common and local staff can rarely provide effective technical support in this area. We found it difficult to obtain adequate assistance on problems related to purchase of parts, use of the dial-tone interface, proper orientation of directional antennae, and mysterious regional service failures that occurred on occasion.
The manufacturer of the CT was also poor at providing timely and effective technical assistance. Information such as the CT power requirements and how to match CT with the various versions of the dial-tone interface was difficult if not impossible to obtain from the manufacturer. Technical support for analog CT service is even less reliable today because the newer digital and multiphase phone technologies now dominate the commercial marketplace.

Operational support is provided by local service providers and includes assistance with equipment purchase and repair, and billing. We found operational support to be unsatisfactory on several levels. Perhaps most frustrating was the gross incompetence exhibited by local providers in the area of billing. We experienced repeated incidences where bills were sent to the wrong address and thus were not received for several months. During one such incident, service was disconnected to five station phones for nonpayment of bills that were never received. Another regular problem was the appearance of phantom charges on bills, with no explanation. Calls to providers seeking explanation of these charges often go unanswered for weeks while the company adds late fees to subsequent bills and threatens to suspend service.

**Summary**

Cellular telephones have proved to be an effective telecommunications option for remote automated weather stations in Arizona. Use of CT has reduced telecommunications costs and provided greater flexibility when siting weather stations. Data retrieval is slightly less reliable with CT than with LTL, but these problems can be overcome by using communications software with redundant calling routines (in case the primary data retrieval call fails) and effective error checking. The major technical hurdle when using CT is to ensure station power supplies are adequate to handle the high power requirement of the CT. Overall, the positive aspects of using CT for station telecommunications offset the rather poor technical and operational support provided by local CT service providers and the manufacturer of the CT.

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Direct Linkage to Stations through the Internet

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Abstract

The Louisiana AgriClimatic Information System (LAIS) was originally designed to provide weather and climate information for agricultural research; its scope has now expanded to include users involved in agricultural, environmental, and emergency management. As a result of this expansion, it was necessary to upgrade the LAIS weather stations to a near real-time data collection system. Since most of the stations are located at Louisiana Agricultural Experiment Station (LAES) sites, which are connected to a statewide network through Internet connections, plans were implemented to equip each station with a computer connected to the local area network and having a serial link from the computer to the data logger; a software system to transfer locally stored data from the computers to a central data archive and access facility at Louisiana State University (LSU) also was developed. This system is now operational at 20 sites across Louisiana.

LAIS must occasionally deal with problems such as stations disappearing and reappearing from client view and, more rarely, transmission problems. System design solutions have been implemented that deal with these network imperfections, such as methodologies that ensure collection of a complete series of data observations. Methods to monitor network reliability are also in place.

Data transferred to the central data archive are immediately available to users. Users can access daily and hourly data listings; daily, hourly, and 5-minute time-series data plots; and hourly station model plots for LAIS weather stations. Several options are available for displaying these products.

Introduction

The Louisiana AgriClimatic Information System (LAIS)\(^1\) weather stations are located on properties operated by the Louisiana Agricultural Experiment Station (LAES), United States Department of Agriculture (USDA), Southeastern Louisiana University, Louisiana Universities Marine Consortium (LUMCON), Laser Interferometer Gravitational-Wave Observatory (LIGO), and R&D Research (private ownership). Originally, the LAIS was owned, solely, by the LAES and was designed to provide weather and climate information for agricultural research. In the past few years this role has expanded to include users involved in agricultural, environmental, and emergency management. These users require more timely access to the data collected at these stations, which resulted in a need to upgrade the LAIS to a near real-time data collection system. Most of the upgrade was an investment in communications equipment and software systems to accommodate the flow of near real-time data.
Communicating with weather station data loggers at remote locations provides a system designer with many different telecommunication options. Most methods provide reliable communication links, but there are often tradeoffs that involve initial acquisition costs, a wide range of ongoing communication fees, and varying levels of routine maintenance and reliability issues. A designer must weigh these factors against the need for timely access to the data logger information.

At the same time that the need for near real-time data access to LAIS stations arose, the LAES was investing in the communications infrastructure at its experiment stations. The experiment stations were connected to the statewide Louisiana Network (LaNet) via dedicated low-speed Internet connections. Additionally, a local area network was installed at each experiment station. Since most of the LAIS weather stations were located on experiment station properties, the opportunity arose to use this Internet system as a data collection framework.

A plan was developed for each station that included a computer connected to the local area network, a serial link from the computer to the weather station data logger, and development of a software system to collect locally stored data from the computers and transfer them to a central data archive and access facility at LSU. The plan was submitted as an environmental management proposal and was funded by the Louisiana Board of Regents. The system is now operational at 20 sites across Louisiana.

**Communication System Description**

The weather stations included in this project consist of Campbell Scientific CR23X microloggers with sensors to measure air temperature (primary and backup), relative humidity, soil temperature at 4 depths, rainfall (primary and backup), wind speed (2 heights), wind direction (2 heights), barometric pressure, solar radiation, and photosynthetically active radiation. Observations from sensors are output to final storage on the data logger at 1-minute (event-based rainfall only), 5-minute, hourly, and daily (8 AM–8 AM and midnight–midnight) intervals. The data loggers communicate with local data collection computers via (1) short-haul modems, (2) spread-spectrum radio modems, and (3) telephone modems where options 1 and 2 were impractical. The local data collection computers collect data from the data loggers using Campbell Scientific PC208W software and store the data in a local master observation file. The master observation file is checked every few seconds for new observations. If a new observation is found, it is appended to a local data cache file that is a temporary collection point for new observations. The master observation file is left unchanged and serves as a local data archive.

Data archived locally is of limited use for a statewide system of weather stations serving a need for near real-time data. The data need to be available at a central location for dissemination to a broad audience of users. A data collection/concentrator computer for the entire LAIS system was developed on the Louisiana State University campus to serve as a central location for data quality control, product generation, and dissemination.

This computer runs an Inter-Language Unification (ILU) client program that generates a network data request to a server program, an ILU ORB (Object Request Broker), running
on each LAIS computer connected to a data logger. When the server receives a request from the client, it sends its recent observations, located in the local data cache file, to the requesting client program. On receipt of a message indicating successful data transfer, the server deletes the local cache file and terminates the network connection.

The client then processes the collected data received from the system of distributed servers. It parses the received data, performs a quality control analysis, and stores the data into netCDF data archives, organized as time-series observation files for each station. The client program polls the stations in its station list until all stations in the system have been contacted. If the network connection to a computer is unavailable, the attempt to connect is aborted and connection to the next station in the list is attempted. The polling cycle is repeated at a predetermined pause interval that is currently set to 5 minutes. Since the client collects data from the stations serially (it won’t poll a station until its predecessor in a processing list has been polled for data), the time between a particular station being polled will be somewhat more than the pause interval. In fact, because of network irregularities, this time may not always be constant. If desired, the client could be configured to continuously poll the server computers (pause time = 0).
Public data communication networks are not perfect and problems do occur. Stations can disappear and reappear from the view of the client, sometimes even during transmission of data from the server to the client. System design solutions to cope with these network imperfections have been implemented. Each time a station is polled, a completely new connection between the client and server computers is initiated. It is more reliable to test and detect a networking problem, or failure of a networked data server, by testing the connection each time the server is polled rather than assuming that the network connection is available. If a connection to a server cannot be established, the client simply skips that station and moves on to the next. After several unsuccessful attempts to a particular station in its station list (the number of failed attempts being a configurable parameter), an e-mail message is sent to one or more data managers, notifying them of the problem. The message includes system diagnostic messages that enable the data manager to take actions to correct the problem.

Transmission problems that occur during the transfer of data from the server to the client are rare, but must be considered in the system design. When the data are properly received from the server, the client sends a verification of the data transmission. When the server receives this verification, it deletes the data (already sent to the client) from its local data cache file. If the server does not receive verification from the client, the local data cache file remains unchanged. During the next request to the station server from the client, the data cache will contain the data that was not transmitted reliably during the previous session plus new data observations written to the local cache file. Using this schema, transmission of a complete set of observations is assured.

An effort to standardize the format of observations at all weather station observations was attempted but finally abandoned. Although a minimum set of sensors is maintained at all LAIS stations, some of the stations collect observations from specialized sensors such as pan evaporation water level, water level in tidal basins, water salinity, leaf wetness, and other variables. Therefore, the format of the data observations sent from a data collection server computer to the data collection/concentrator client can vary. A flexible method to handle these differences was accomplished through the use of data set/data type definition files that reside on the client computer. Data collection formats can be altered at any time by creating new data-type definition files on the client that match the data format transmitted by the servers. These files contain the type and order of each datum as well as the units for the observations. In the same manner, quality control information is loaded from definition files. A file is stored on the client computer for each weather station and includes information on maximum and minimum acceptable values for each observation and physical relationships that exist between observations contained in the same observation record.

Another method to monitor the status of network communications was needed to determine overall network reliability. A web-based application was developed that polls each server in the LAIS to determine if the network connection to the server is active. A color-coded display allows an operator to quickly determine the status of a connection to any server. Weather data are not collected during this process, which is solely intended to determine the status of network connections to remote server processes.
Near Real-time Product Generation

Data transferred from a server to the LSU client computer are immediately available in the data archives of the client. A web browser interface has been developed that allows privileged users to access daily and hourly data listings; daily, hourly, and 5-minute time-series data plots; and hourly station model plots for LAIS weather stations. Users can specify the time interval for these product types and can choose data elements and data units that are displayed on the products. Graphical products are generated dynamically from user inputs using the Grid Analysis and Display System (GrADS)3 data plotting package.

Results and Summary

The system developed to retrieve near real-time information from remote LAIS weather stations has provided enhanced weather and climate information for agricultural, environmental, and emergency managers. The data retrieval routines are robust and provide a
reliable methodology to access remote data collection platforms in a cost-effective manner.

Some problems in the system remain to be rectified. The network connections to the rural LAES sites are often unreliable and cause intermittent delays in acquiring near real-time data access. The design methodologies implemented to ensure collection of a complete time series of data observations, however, have been successful. Another problem area is the use of Microsoft Windows operating systems for the remote data servers. These systems require occasional rebooting to recover from halted program processes that prevent connection to the ILU server process. An enhancement that would stabilize these processes would require design and development of a local data collection process that would replace the Campbell Scientific PC208W data logger interface program and eliminate the dependence on a Microsoft Windows server. The authors envision a system of LINUX data servers that would provide enhanced server reliability and allow for improved management and configuration of the remote data servers.

Notes
1The LAIS home page is available at http://typhoon.baed.edu/.
2Available at http://www.state.la.us/otm/lanet/.
3The Campbell Scientific home page is available at http://www.campbellsci.com/.
Site Selection and Network Density
Station Wind Characterization

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Abstract
The effects of topography and obstructions can result in significant differences in wind observations at neighboring or distant stations in a weather station network. These effects make it difficult to make comparisons of wind data between stations. Application of the wind data to areas between the stations, a practice often required when evaluating wind damage, chemical drift, and estimating wind speed at a height different from the measurement for siting wind generators for alternative energy production, is compromised. Detailed descriptions of the topography and obstructions surrounding a weather tower may be used to help remove exposure effects from the wind measurements. Descriptions must include the distance of the obstruction from the tower, the obstruction height and breadth, and the density of the object. Vegetation descriptions in the vicinity of the station must, at the minimum, include height, breadth, and vegetation type (deciduous or evergreen). Examples from the Illinois Climate Network show the importance of selecting the appropriate site for a station to minimize the exposure effects of topography, buildings, trees, and other obstructions. Although failure to minimize these effects may limit the application of the data, it does not invalidate the data collected at the site.

Introduction
The objective of a single weather station is to measure weather conditions at a specific location. Station networks include this objective and the objectives of comparing weather at different stations and interpolating weather conditions between stations. When wind is being measured at a single station solely to characterize the wind at that location and at the height of the instrument, no additional observations need to be made. However, application of wind observations at a given location often requires estimating wind speeds and directions at different heights and locations in the area surrounding the weather tower. Therefore, a station site must be characterized by its surroundings to understand how obstructions affect the wind flow at the station.

The World Meteorological Organization standards (WMO, 1983) require that wind measurements for synoptic purposes be measured at, or referenced to, a height of 10 meters (m) over open terrain. Open terrain is defined as an area where the distance between the anemometer and obstructions is at least ten times the height of the obstructions. With these standards, an acceptable site can be found in most areas. However, studies by Schmid and Oke (1990) and Wieringa (1992) show that large obstructions and terrain changes as far away as 5 km can affect the wind flow at a station. Thus, stations that meet the WMO synoptic standard may not truly represent the synoptic wind in a region.

With the concern about global change due to the doubling of carbon dioxide in the atmosphere and the potential future mandating of carbon emission reductions, alternative energy from wind becomes more attractive. Proper siting and sizing of wind generators may
require the use of wind data from the various weather mesonets that exist around the country. This will require accurate characterization of the sites for wind obstructions.

The objectives of this chapter are to describe how obstructions affect the wind at a weather station, to provide a simple method of estimating the impact of these obstructions on wind flow at the anemometer, and to suggest a procedure for describing and documenting the wind characteristics of a weather station location. It is assumed throughout this chapter that the anemometer is located at a height of 10 m.

**Wind Obstructions**

As air moves along the surface of the earth, various objects on the surface obstruct the flow of the air near the ground. Obstructions to the flow of wind include buildings, fences, vegetation, and terrain variations. The magnitude of these influences on wind flow depends on the porosity, height, and breadth of the obstacle. Oke (1978) described these effects (Figures 1–3). Wind flow over a solid barrier (Figure 1) results in four flow zones. The undisturbed flow occurs upwind and over the top of the barrier at approximately 3 times the barrier height. In the displacement zone, wind speeds are increased a distance of 0 to 3 barrier heights upwind and above the barrier, and approximately 10 barrier heights downwind from the barrier in a region 1 to 3 barrier heights above the surface. Just downwind of the barrier is a cavity zone where the wind direction reverses near the surface. This zone is also called the separation bubble, or lee eddy. The fourth zone is the wake zone and is an area of increased turbulence. The wake zone extends downwind to a distance greater than 15 times the barrier height.

The zones can also be seen around individual plants or plants in a row such as a windbreak or shelterbelt. The lee eddy develops only when the shelterbelt is very dense (Figure 2). With decreasing shelterbelt density, the lee eddy becomes weaker and eventually disappears (Oke, 1978). The turbulent wake is the largest when the shelterbelt is of medium density.

The vertical flow patterns around buildings are similar to those around a barrier or shelterbelt (Figure 3). The displacement, cavity, and wake zones can also be seen in the horizontal flow around the building (Figure 3c, d). This displacement in the horizontal results in a wind shadow of the building larger than the dimensions of the building. When several buildings are located in the vicinity of the anemometer, the turbulence and flow characteristics can become quite complex.

Wind flow over a ridge (Figure 4) can show the same wind zones as other obstructions (Kaimal and Finnigan, 1994). Thus, even the terrain features must be considered as wind obstructions if the data collected at the station are to be extended to the region around the station or to compare the wind at two different stations.

**Estimating Effects of Obstructions**

The unevenness (roughness) of the surface causes a drag on the air flow, which results in reduced wind speed and increased turbulence. Drag is expressed mathematically in terms of a variable with units of length and is related to the height of the obstacles on the surface. The effect of the earth’s surface drag on the synoptic wind flow can be estimated
Figure 1. Flow zones upwind and downwind of a solid barrier. From Boundary Layer Climates by T.R. Oke, 1978, Methuen, New York. Reprinted by permission.

Figure 2. Effect of shelterbelts of different densities on wind. From Boundary Layer Climates by T.R. Oke, 1978, Methuen, New York. Reprinted by permission.
Figure 3. Flow patterns around a sharp-edged building. Side view of (a) streamlines and flow zones, and (b) velocity profiles and flow zones with building oriented normal to the flow. Plan view of streamlines with the building oriented (c) normal, (d) diagonally to the flow. From Boundary Layer Climates by T.R. Oke, 1978, Methuen, New York. Reprinted by permission.

Figure 4. Wind flow over an idealized two-dimensional ridge. From Atmospheric Boundary Layer Flows by J.C. Kaimal and J.J. Finnigan, copyright 1994 Oxford University Press, Inc. Used by permission of Oxford University Press, Inc.
by evaluating the roughness \((z_{0\theta})\) in all directions from the anemometer tower. Three different methods of evaluating \(z_{0\theta}\) are described in their order of decreasing cost and difficulty of use.

The first method computes \(z_{0\theta}\) after characterizing the roughness in all directions by identifying the number, type, and size of the different obstructions and then measuring the distance from the obstructions to the anemometer. Lettau (1969) suggests a procedure for estimating \(z_{0\theta}\) using the above data. Various obstructions surrounding the anemometer and their distances are documented. Accurate computation of the roughness length for each direction requires a complex model (Schmid and Oke, 1990) that accounts for all obstructions and roughness parameters within 5 km of a station. The difficulty and cost in this method are the computations and the detailed characterization of the obstructions.

The second method involves measuring wind speed at several heights at the location and computing \(z_{0\theta}\) from the profile data. The costs here are the anemometers at multiple heights.

The third method uses an engineering approximation proposed by Lumley and Panofsky (1964) to compute \(z_{0\theta}\). In this approximation, the standard deviation of the wind speed \((\sigma_s)\) at the anemometer height \((z_s)\) is given by

\[
\sigma_s = \frac{U_s}{\ln(z_s/z_{0\theta})}
\]  

(1)

where \(U_s\) is the mean wind speed and \(z_s\) is the anemometer height. If hourly measurements of wind speed and direction are available, the azimuth sector roughness characteristics can be estimated by solving Eq. 1 for \(z_{0\theta}\). Lumley and Panofsky (1964) suggest using only those hourly observations with mean wind speeds greater than 3 ms\(^{-1}\). This threshold reduces the atmospheric stability effects on the observed wind speeds. By dividing the yearly data into different seasons, it is possible to study the variation in seasonal roughness lengths. These effects can be significant in regions where deciduous trees or seasonal crops constitute a major portion of the landscape.

To compare different stations to each other, the roughness and anemometer height need to be corrected to a standard reference. The suggested standard reference (Wieringa, 1993) is an anemometer height of 10 m over flat open terrain with a reference roughness \((z_{0r})\) of 0.03 m. The reference or “exposure corrected” wind speed \((U_r)\) can be computed by

\[
U_r = U_s \frac{\ln(60 / z_{0r}) \ln(10 / z_{0r})}{\ln(z_s / z_{0r}) \ln(60 / z_{0r})}
\]

(2)

where 60 represents the height in meters where it is assumed the roughness effects are no longer effective. This method provides a good first approximation of the suitability of a site for representing winds in the surrounding area, and an initial correction to wind records.

Accurate estimation or modeling of the effects of obstructions on wind flow requires complex mathematics (Oke, 1978; Kaimal and Finnigan, 1994) that are beyond the scope of this chapter.

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Describing and Documenting Station Obstructions

Every attempt should be made to locate new stations in “ideal” locations. The ideal location would be a site with a large flat fetch with short vegetation. However, existing stations in most cases are compromised in one or more ways. Quite often the selection of the site is negotiated with a landowner, which means that the station cannot be located at the ideal site. If phone service or AC power is required to power the station, then the likelihood of some obstruction affecting the station is greatly increased. Therefore, a complete description of any obstructions that are closer to the anemometer tower than 30 times the height of the obstruction should be developed (Oke, 1978). Even “ideal” locations should have a site description so that it is clear that there are no obstructions. With the availability of solar panels to provide power for the instruments, and the new bandwidth technology for improved communication for data retrieval, selection of more ideal sites should be possible.

The station description should include an aerial photograph, a topography map of the area surrounding the station, and a map and description of the obstructions. Obstruction descriptions can be as simple as “a building is located within X meters and is Y meters tall and Z meters wide.” Trees should be described as either evergreen needle or broad-leaf, or deciduous. Shelterbelts or natural tree stands should also be identified and their density characterized.

Aerial photographs are valuable in that they provide a clear indication of the general vegetation and building clusters surrounding the station. The DeKalb, Bondville, and Belleville Illinois Climate Network (ICN) stations are located on flat terrain, with no major terrain changes within 1 km of each of the stations. Aerial photographs of DeKalb and Bondville (Figure 5) and Belleville (Figure 6) show the major obstructions within 1 km of each of the weather towers.

Figure 5. Aerial photograph of DeKalb (left) and Bondville (right) Illinois Climate Network stations. The photographs are 2 km on each side. Weather towers are located at the point of the arrows at the centers of the photographs.
Figure 6. Aerial photograph of Belleville (left) and Dixon Springs (right) Illinois Climate Network stations. The photographs are 2 km on each side. Weather towers are located at the point of the arrows at the centers of the photographs.

At DeKalb, experiment station buildings and an evergreen windbreak are located from the west to approximately north of the weather tower (Figure 5). The windbreak is approximately 10 times its height away from the tower. At Bondville there is a small farmstead approximately 150 m east-northeast of the weather tower.

At Belleville, a small river with an associated forested area is located approximately 275 m east of the weather tower (Figure 6). A single-row tree windbreak is also located 125 m west of the weather tower. Other obstructions near the station are buildings and single trees. All of the single trees and buildings are less than 10 m tall.

Both the Dixon Springs (Figure 6) and Stelle (Figure 7) stations are located on rolling terrain. In addition to the rolling terrain, the Dixon Springs station is located in an area of scattered forest. The trees in the forest are 10 to 15 m tall and on the east side of the tower are as close as 30 m. At Stelle, the maximum elevation change within 1 km of the weather tower is 10 m (Figure 7, topographic map). Northeast of the Stelle weather tower is the community of Stelle, comprising homes and landscape plants.

A complete written description and map of the obstructions (buildings, trees, etc.) near the weather tower should be developed. The description of the obstructions should include the height, breadth, and distance from the weather tower. These descriptions should also be accompanied with pictures in all directions from the tower, looking away from the tower. Pictures should be taken from ground level as well as from the anemometer height. Descriptions for all the ICN stations have been made (Hollinger et al., 1994).

The effects of the different obstructions at DeKalb, Bondville, Belleville, Dixon Springs, and Stelle sites are estimated for each 22.5-degree sector around the weather tower by computing the roughness length using Eq. 1 and solving for $z_{0w}$. The average roughness length in 16 sectors at the DeKalb station (Figure 8) shows the effects of the buildings and
Figure 7. Aerial photograph and topographic map of the Stelle Illinois Climate Network station. The photograph is 2 km on each side, and the circle on the topographic figure is 2 km in diameter.

windbreak to the west and northwest of the station. Clockwise from the east-northeast (ENE) sector through the southwest (SW) sector, the average annual roughness length ranges from 0.10 to 0.12 m. In these sectors, the area around the DeKalb station is characterized by flat plowed fields with scattered farmsteads at a distance greater than 0.5 km from the weather tower. Clockwise from the west-southwest (WSW) sector through north (N), the roughness length ranges from 0.17 to 0.71 m. The largest roughness lengths are located in the west (W), west-northwest (WNW), northwest (NW) and north-northwest (NNW) sectors. These four sectors incorporate the experiment station buildings and windbreak and have an average roughness length of 0.57 m. The largest roughness length is located in the NW sector where the evergreen windbreak extends across the entire sector. The obstructions are not located within the N and WSW sectors, but these sectors show a larger roughness length than the NNE and SW sectors that have similar features. The larger roughness lengths in the N and WSW sectors are due to the windbreak's and buildings' aerodynamic breadth (Figure 3).

Figure 8. Average estimated roughness lengths in the sixteen 22.5-degree sectors around the DeKalb Illinois Climate Network station.
Table 1. Estimated roughness length (meters) in 22.5-degree azimuth sectors around the De Kalb Illinois Climate Network station.

<table>
<thead>
<tr>
<th>Azimuth</th>
<th>Sector</th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>Average</th>
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</tbody>
</table>

Seasons have a large effect on the roughness length at all the stations. At De Kalb, in the sectors most affected by the windbreak (WNW and NW), the seasonal effect is small (Table 1). This is because of the relatively constant density of the evergreen windbreak. In the other sectors that include deciduous trees and plants (W, NNW), the seasonal effects are more pronounced. In these sectors, the mean summer roughness is 2 times greater than the winter roughness. In the sectors that are not affected by obstructions, the roughness length increases from an average of 0.03 m in the winter to 0.21 m in the summer. This increase in the summer is due to the growth of corn and soybean and represents a typical roughness length for these crops.

The Bondville station is closer to an ideal location for wind measurements than any other ICN station. The mean annual roughness lengths range from 0.09 to 0.14 m. The largest roughness lengths are located in the ENE and E sectors, where a farmstead is located approximately 150 m from the weather tower. As with all ICN stations, the roughness lengths are smallest in the winter. Spring roughness lengths are smaller than the autumn roughness lengths, and both are smaller than the summer roughness length (Table 2). At Bondville, the mean roughness length is 0.03 m in the winter and 0.18 m in the summer. The smallest roughness lengths are located in the S, SSW, and SW sectors (Table 2). These sectors are flat with a short grass surface, which is mowed in the summer. The other sectors have corn and soybean crops.

The effects of the forested area E of the Belleville station and the windbreak to the SSW and W can also be observed in the estimated roughness lengths (Table 3). The forest
Table 2. Estimated roughness length (meters) in 22.5-degree azimuth sectors around the Bondville Illinois Climate Network station.

<table>
<thead>
<tr>
<th>Azimuth</th>
<th>Sector</th>
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<td>292.5</td>
<td>WNW</td>
<td></td>
<td>0.03</td>
<td>0.08</td>
<td>0.19</td>
<td>0.10</td>
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</tr>
<tr>
<td>315.0</td>
<td>NW</td>
<td></td>
<td>0.03</td>
<td>0.09</td>
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<td>0.14</td>
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</tr>
<tr>
<td>337.5</td>
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<td>0.04</td>
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</tr>
<tr>
<td>Season Average</td>
<td></td>
<td></td>
<td>0.03</td>
<td>0.07</td>
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<td>0.12</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 3. Estimated roughness length (meters) in 22.5-degree azimuth sectors around the Belleville Illinois Climate Network station.

<table>
<thead>
<tr>
<th>Azimuth</th>
<th>Sector</th>
<th>Season</th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>Average</th>
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<tbody>
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<td>0.63</td>
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<td>0.33</td>
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</tr>
<tr>
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<td>0.16</td>
<td>0.23</td>
<td>0.15</td>
<td>0.17</td>
</tr>
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<td>SSE</td>
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<tr>
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<td>0.06</td>
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<tr>
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<td>0.19</td>
</tr>
<tr>
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<td>0.41</td>
<td>0.48</td>
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<td>0.39</td>
</tr>
<tr>
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<td>0.91</td>
<td>0.48</td>
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<td>0.54</td>
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<td>0.35</td>
</tr>
<tr>
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<td>0.17</td>
<td>0.34</td>
<td>0.18</td>
<td>0.19</td>
</tr>
<tr>
<td>315.0</td>
<td>NW</td>
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<tr>
<td>337.5</td>
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<td></td>
<td>0.08</td>
<td>0.16</td>
<td>0.25</td>
<td>0.13</td>
<td>0.16</td>
</tr>
<tr>
<td>Season Average</td>
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<td></td>
<td>0.16</td>
<td>0.25</td>
<td>0.38</td>
<td>0.26</td>
<td>0.26</td>
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</table>
Table 4. Estimated roughness length (meters) in 22.5-degree azimuth sectors around the Dixon Springs Illinois Climate Network station.

<table>
<thead>
<tr>
<th>Azimuth</th>
<th>Sector</th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>0.45</td>
<td>0.68</td>
<td>0.50</td>
<td>0.50</td>
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<tr>
<td>22.5</td>
<td>NNE</td>
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<td>0.75</td>
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<td>1.20</td>
<td></td>
<td></td>
<td>1.06</td>
</tr>
<tr>
<td>67.5</td>
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<td>0.92</td>
<td>1.48</td>
<td></td>
<td></td>
<td>1.20</td>
</tr>
<tr>
<td>90.0</td>
<td>E</td>
<td>0.88</td>
<td>1.08</td>
<td></td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>112.5</td>
<td>ESE</td>
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<td></td>
<td></td>
<td></td>
<td>0.84</td>
</tr>
<tr>
<td>135.0</td>
<td>SE</td>
<td>0.84</td>
<td>0.81</td>
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<td>0.79</td>
<td>0.81</td>
</tr>
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<td>SSE</td>
<td>0.85</td>
<td>0.89</td>
<td></td>
<td>0.88</td>
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</tr>
<tr>
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<td>0.77</td>
<td>1.01</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>202.5</td>
<td>SSW</td>
<td>0.59</td>
<td>0.72</td>
<td>1.31</td>
<td>0.93</td>
<td>0.89</td>
</tr>
<tr>
<td>225.0</td>
<td>SW</td>
<td>0.39</td>
<td>0.52</td>
<td>0.95</td>
<td>0.75</td>
<td>0.65</td>
</tr>
<tr>
<td>247.5</td>
<td>WSW</td>
<td>0.16</td>
<td>0.33</td>
<td>0.50</td>
<td>0.40</td>
<td>0.35</td>
</tr>
<tr>
<td>270.0</td>
<td>W</td>
<td>0.24</td>
<td>0.31</td>
<td>0.40</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>292.5</td>
<td>WNW</td>
<td>0.23</td>
<td>0.45</td>
<td>0.49</td>
<td>0.32</td>
<td>0.37</td>
</tr>
<tr>
<td>315.0</td>
<td>NW</td>
<td>0.21</td>
<td>0.25</td>
<td>0.27</td>
<td>0.23</td>
<td>0.24</td>
</tr>
<tr>
<td>337.5</td>
<td>NNW</td>
<td>0.22</td>
<td>0.28</td>
<td>0.36</td>
<td>0.34</td>
<td>0.30</td>
</tr>
<tr>
<td>Season Average</td>
<td>0.50</td>
<td>0.68</td>
<td>0.71</td>
<td>0.58</td>
<td>0.66</td>
<td></td>
</tr>
</tbody>
</table>

*Excluding missing sectors.

affects the sectors extending in a clockwise direction from the NNE sector through the ESE sector (Figure 6). In these sectors the mean annual roughness length is 0.34 m. In the winter, when the trees do not have leaves, the average roughness length for these five sectors is 0.25 m. In the summer, when the trees have leaves, the roughness length increases to 0.48 m, a 92% increase. A larger increase is seen in the WSW and W sectors that are affected by a windbreak. The roughness length is 0.28 m in the winter and 0.73 m in the summer, a 164% increase. This windbreak is comparable to the windbreak at De Kalb, except the windbreak at Belleville comprises deciduous trees instead of evergreen trees. These differences show the importance of identifying the type of vegetation in the vicinity of a weather tower.

An example of a station that is poorly sited is the Dixon Springs station. Although the data represent the immediate locale of the station, extension of the data to surrounding areas must be done with caution. The mean annual roughness lengths at Dixon Springs range from 0.24 to 1.20 m (Table 4). There are sectors with missing roughness lengths at Dixon Springs. These sectors had computed roughness lengths greater than 2 m and were computed on limited data. The missing sectors had dense deciduous tree stands within 100 m of the weather tower. This station location was selected so that it was collocated with a National Weather Service Cooperative station, and power and phone lines were available to the site. The location of the Dixon Springs station is an example of the con-
Table 5. Estimated roughness length (meters) in 22.5-degree azimuth sectors around the Stelle Illinois Climate Network station.

<table>
<thead>
<tr>
<th>Azimuth</th>
<th>Sector</th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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<td>0.05</td>
<td>0.11</td>
<td>0.22</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>22.5</td>
<td>NNE</td>
<td>0.05</td>
<td>0.12</td>
<td>0.16</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>45.0</td>
<td>NE</td>
<td>0.05</td>
<td>0.10</td>
<td>0.17</td>
<td>0.14</td>
<td>0.12</td>
</tr>
<tr>
<td>67.5</td>
<td>ENE</td>
<td>0.07</td>
<td>0.09</td>
<td>0.17</td>
<td>0.13</td>
<td>0.12</td>
</tr>
<tr>
<td>90.0</td>
<td>E</td>
<td>0.04</td>
<td>0.06</td>
<td>0.14</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td>112.5</td>
<td>ESE</td>
<td>0.06</td>
<td>0.05</td>
<td>0.18</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>135.0</td>
<td>SE</td>
<td>0.07</td>
<td>0.07</td>
<td>0.16</td>
<td>0.09</td>
<td>0.10</td>
</tr>
<tr>
<td>157.5</td>
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<td>0.06</td>
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<td>0.15</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>180.0</td>
<td>S</td>
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<td>0.07</td>
<td>0.14</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>202.5</td>
<td>SSW</td>
<td>0.06</td>
<td>0.07</td>
<td>0.14</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>225.0</td>
<td>SW</td>
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<td>0.07</td>
<td>0.13</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>247.5</td>
<td>WSW</td>
<td>0.03</td>
<td>0.09</td>
<td>0.10</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>270.0</td>
<td>W</td>
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<td>0.08</td>
<td>0.14</td>
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<td>0.08</td>
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<tr>
<td>292.5</td>
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</tr>
<tr>
<td>315.0</td>
<td>NW</td>
<td>0.03</td>
<td>0.09</td>
<td>0.17</td>
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<tr>
<td>337.5</td>
<td>NNW</td>
<td>0.04</td>
<td>0.09</td>
<td>0.14</td>
<td>0.12</td>
<td>0.10</td>
</tr>
<tr>
<td>Season Average</td>
<td>0.05</td>
<td>0.09</td>
<td>0.16</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
</tr>
</tbody>
</table>

The annual roughness lengths at the Stelle station are relatively constant, with a range from 0.08 to 0.13 m (Figure 9). This indicates the general uniformity of vegetation and topography around the weather station. The largest roughness lengths are located in the N, NNE, NE, and ENE sectors. These sectors include the community of Stelle, with its buildings and landscape plants. The effect of topography at Stelle can be seen when the mean winter roughness (Table 5) is compared to

Figure 9. Average estimated roughness lengths in the sixteen 22.5-degree sectors around the Stelle Illinois Climate Network station.
the mean winter roughness at Bondville (Table 2). The winter roughness length at Stelle is 0.05 m, compared to 0.03 m at Bondville. Both stations are relatively free of obstructions, with the only difference being the small rolling hills at Stelle compared to the flat terrain at Bondville. Although this correction is small, a measured wind speed of 5 m s⁻¹ at Stelle would have a wind speed, corrected for topographic effects, of 5.1 m s⁻¹. At Bondville, no topography correction is required.

Summary

The effects of topography and obstructions can result in significant differences in wind observations at neighboring or distant stations in a weather station network. These effects make it difficult to make comparisons of wind data between stations and apply the wind data to areas between the stations, a practice often required when evaluating wind damage and chemical drift and estimating wind speed at a height different from the measurement for siting wind generators for alternative energy production. The topography and obstructions surrounding a weather tower must be described in detail to remove their effects from the wind measurements. Descriptions must include the distance from the station, the obstruction height and breadth, and the density of the object. Vegetation descriptions in the vicinity of the station must, at a minimum, include their height, breadth, and vegetation type (deciduous or evergreen). Examples from the Illinois Climate Network show the importance of selecting the appropriate site for a station to minimize the exposure effects of topography, buildings, trees, and other obstructions. Although failure to minimize these effects may limit the application of the data, it does not invalidate the data collected at the site.

References

Illustration of Flux Footprint Estimates Affected by Measurement Height, Surface Roughness, and Thermal Stability

George Burba
School of Natural Resource Sciences, University of Nebraska, Lincoln

Abstract

The dependence of the flux footprint on measurement height, surface roughness, and thermal stability is illustrated in the example of the latent heat flux measured on two days during the growing season of 1999 over a tallgrass prairie community. Absolute values of latent heat flux contributed from a certain upwind distance are given along with cumulative contributions. The extent of differences in flux footprint is demonstrated for 1.5 and 4.5 m measurement heights, 0.05 m and 0.6 m vegetation heights, and near-neutral, stable, and unstable conditions. Interaction between effects of measurement height and roughness on footprint is also shown. Important practical implications of the described effects are stated in terms of sufficient fetch requirement and “no contribution zone” constraint in the immediate surroundings of the flux station.

Although automated weather stations are not necessarily flux stations, some of the implications for fetch requirement are worthy of consideration when siting discussions are to be made.

Introduction

Measurements of surface fluxes of heat, water vapor, carbon dioxide, and other gases provide crucial information for climate and weather modeling, hydrology, agriculture, GIS, and remote sensing applications. In the majority of the cases, data provided from flux measurement stations are employed to represent certain geographic areas (e.g., ecosystem, vegetation community, agricultural lands), even though actual measurements were taken at one or a few flux stations within this area. Questions of “representativeness” of flux measurements were addressed in terms of fetch (Gash, 1986; Heilman et al., 1989; Horst and Weil, 1994; Stannard, 1997), ground-level source or source area (Elliot, 1961; Nieuwstadt and Ulden, 1978; Horst, 1979; Grynning et al., 1983; Schmid, 1994), and footprint (Leclerc and Thurtell, 1990; Schuepp et al., 1990; Horst and Weil, 1992; Finn et al., 1996). Each of these terms (even though slightly different in exact meaning) describes the characteristics of the upwind area, which is expected to influence most of the downwind measurements at a certain height.

Concept of footprint, related terms, theoretical assumptions, and a review of models for footprint estimation are given in Leclerc and Thurtell (1990), Schuepp et al. (1990), Horst and Weil (1992), and Finn et al. (1996). Continuing the footprint topic, the objective of this presentation is to demonstrate the extent of footprint effect using field data, and to go over the main points of the footprint effect on the flux measurements. In particular, effect of measurement height and roughness and their interrelation are demon-
strated for the example of latent heat flux measurements in near-neutral conditions. Effect of stability is also described.

Materials and Methods

Study Site
The study was conducted over native tallgrass prairie (36°56' N, 96°41' W, elev. 350 m) located in north-central Oklahoma. The site (500 x 500 m) is surrounded by rolling hills occupied by true grasses (e.g., little bluestem, side oats grama, blue grama, and big bluestem).

The eddy correlation measurements of latent heat flux were conducted at the height of 4.5 m above the soil surface. Instruments included a three-dimensional sonic anemometer (Gill Instruments Ltd., Lymington, England) and a krypton hygrometer (Campbell Scientific, Logan, Utah). Further details on the instrumentation and setup can be obtained from the studies of Verma et al. (1989) and Verma (1990).

Mean air temperature and humidity were measured with Vaisala temperature/humidity sensors (Vaisala Inc., Woburn, Massachusetts, model Humiter 50Y) at the height of 4.5 m and 1.5 m. Mean horizontal wind speed (U) was measured at 4.5 m and 1.5 m above the soil surface with cup anemometers (Met One, Grants Pass, Oregon, model 010C). Wind direction was measured with a vane (Met One, Grants Pass, Oregon) at the height of 5 m.

Theoretical Considerations
Cumulative normalized contribution to flux measurement (CNF) was computed from analytical solutions of the diffusion equation for near-neutral conditions following Schuepp et al. (1990) and Gash (1986):

$$CNF(x_L) = -\int_0^{x_L} \frac{U(z-d)}{u_* k x^2} e^{-\frac{U(z-d)}{u_* k x_L}} dx = e^{-\frac{U(z-d)}{u_* k x_L}},$$  \hspace{1cm} (1)

where
x_L is distance from the station, m
U is mean integrated wind speed, m s^{-1}
z is measurement height, m
u_* is friction velocity
d is zero plain displacement, m
k is von Karman’s constant (= 0.4)
e is base for the natural logarithm system (= 2.71)

The ratio of U/u_*, was computed from the z, d, and surface roughness parameter (z_0) as follows (Schuepp et al., 1990):

$$\frac{U}{u_*} = \frac{\ln((z-d)/z_0)-1+z_0/(z-d)}{k(1-z_0/(z-d))}$$  \hspace{1cm} (2)
Zero plain displacement was computed using the equation described in Rosenberg et al. (1983):

\[
\frac{U}{u^*} = \frac{\ln \left( \frac{z - d}{z_0} \right)}{k},
\]

where \(z_0\) was computed from canopy height following Szeicz et al. (1969).

**Results and Discussion**

Three main factors affecting the station footprint at a flux measurement site are measurement height, surface roughness, and atmospheric stability (Leclerc and Thurtell, 1990). Below we provide examples of the effect of measurement height and roughness on flux footprint using our field data from the tallgrass prairie site and an approach described in Schuepp et al. (1990). Effect of stability is also described following Leclerc and Thurtell (1990).

To demonstrate the effect of measurement height and roughness in near-neutral conditions, two days were chosen from the growing season of 1999 (Table 1). April 4, 1999, was a clear day shortly after a prescribed burn. With virtually no vegetation, the surface was smooth (with a roughness parameter of about 0.007 m). Thermal stability was near-neutral, with \(z/L\) ranging for most of the day from -0.003 to 0.05. July 30, in contrast to April 7, had a relatively large canopy height of 0.6 m, and a roughness parameter of about 0.08 m. July 30 also had near-neutral conditions, with \(z/L\) ranging for most of the day from -0.08 to 0.2.

**Table 1. Weather conditions and major parameters for two selected days (April 8 and July 30, 1999): tallgrass prairie.**

<table>
<thead>
<tr>
<th></th>
<th>04/08/1999</th>
<th>07/30/1999</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sky</td>
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<td>clear</td>
</tr>
<tr>
<td>ET, mm day(^{-1})</td>
<td>3.8</td>
<td>4.2</td>
</tr>
<tr>
<td>T, (^\circ)C</td>
<td>22.1</td>
<td>30.7</td>
</tr>
<tr>
<td>(U, \text{ m s}^{-1})</td>
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<td>5.2</td>
</tr>
<tr>
<td>Wind dir.</td>
<td>167–261</td>
<td>158–200</td>
</tr>
<tr>
<td>Canopy h, m</td>
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</tr>
<tr>
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<td>“rough”</td>
</tr>
<tr>
<td>Roughness, (z_0)</td>
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<td>0.08</td>
</tr>
<tr>
<td>Stability</td>
<td>near neutral</td>
<td>near neutral</td>
</tr>
<tr>
<td>Range of (z/L)</td>
<td>(-0.003–0.05)</td>
<td>(-0.08–0.2)</td>
</tr>
<tr>
<td>(for most of the day)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Averaged (z/L)</td>
<td>0.009</td>
<td>0.026</td>
</tr>
</tbody>
</table>
Effect of Measurement Height

Relative contributions to latent heat flux are shown as a function of upwind distance on 7/30/99 in Figure 1a. This plot (and following similar plots) shows how much of the total flux came from a given upwind distance such that integration (area below the curve) of the flux contributions by distance (from zero to infinity) would give total ET. When measured at the height of 4.5 m, peak contribution of the ET (0.02 mm) came from the upwind distance of about 60–65 m, while the area within 20 m of the station did not contribute any of the measured flux. In terms of cumulative contribution (Figure 1b), 80% of the total daily flux (3.4 out of 4.2 mm) came from an upwind distance of 20–450 m.

Figure 1. Effect of measurement height on the water vapor flux footprint on July 30, 1999: (a) relative and absolute contribution of the upwind distance to total ET; (b) cumulative contribution of the upwind distance to total ET.

Hypothetical contributions for the same ET are plotted in Figures 1a and 1b for the case if measurements were conducted at the height of 1.5 m. Dramatic change in the contribution is observed. Peak contribution came from an upwind distance of about 12–18 m (versus 60–65 m for the measurement height of 4.5 m). Magnitude of the peak was about 0.09 mm, which is about 4.5 times larger than that for the 4.5 m measurement height. More than 80% of daily ET came from an area within 80 m from the station (versus 20–450 m zone for 4.5 m measurement height, Figure 1b).
Difference in footprints due to measurement height was observed not only near the station but also as far as 500 m away (Figure 1b). For 4.5 m measurement height, only about 81% of the flux came from within 500 m, while for 1.5 m the contribution of the upwind direction within 500 m exceeded 98% (or 4.1 out of 4.2 mm of ET).

Overall, with increased measurement height, upwind distance of peak contribution increased (while magnitude of the peak contribution decreased) and upwind distance covered by the station increased dramatically, as did the zone of “no contribution” around the station. An important practical implication of the effect of the measurement height on flux footprint is that both sufficient fetch and undisturbed area around the instrument are very important for proper footprint at a given measurement height.

**Effect of Roughness**

Effect of roughness on the flux station footprint is demonstrated in Figures 2a and 2b. For the 1.5 m measurement height, the largest contribution came from 12–18 m (2% of ET) on the day with relatively high roughness (7/30/99, canopy height 60 cm). For the same height on the day with low roughness (4/8/99, canopy height <5 cm), peak contribution

![Figure 2](image-url)

**Figure 2.** Effect of surface roughness on the water vapor flux footprint: (a) relative contribution of the upwind distance to total ET; (b) cumulative contribution of the upwind distance to total ET.
shifted to about 30–35 m of upwind distance, and was 2 times smaller (0.01% of ET). In terms of cumulative contribution (Figure 2b), for rough surface more than 80% of the ET (3.4 out of 4.2 mm) came from within 80 m upwind, while for smooth surface the same contribution came from within 250 m. The “no contribution” zone was within 5 m around the station for rough surface, and 10 m for smooth surface.

Overall, with increased roughness the upwind distance of the peak contribution decreased, the magnitude of the peak contribution increased, and the upwind distance covered by the station and the zone of “no contribution” decreased in size, as compared to the “smooth” surface. The important practical implication of the effect of the roughness on the flux footprint is that both sufficient fetch and undisturbed area around the instrument are very important for the proper footprint at any roughness.

**Interaction between Measurement Height and Roughness**

The contribution from the upwind distance for different measurement heights is shown for “smooth” surface (4/8/99) in Figure 3a, and for “rough” surface (7/30/99) in Figure

![Graph](image)

*Figure 3.* Effect of measurement height on the water vapor flux footprint at different roughnesses: (a) relative contribution of the upwind distance to total ET for two measurement heights on April 8, 1999 (“smooth” surface); (b) relative contribution of the upwind distance to total ET for two measurement heights on July 30, 1999 (“rough” surface).
3b. As can be seen from the comparison of the two figures, the “rough” surface measurement height had a more profound effect on footprint than was the case for “smooth” surface. Peak contribution increased 3 times with an increase in measurement height on 4/8/99 (short canopy, smooth surface), while for “rough” surface the same increase in measurement height led to a peak contribution increase of 5 times. Upwind distance to the peak contribution increased about 3 times (with increased measurement height) in both cases of roughness.

Contribution from the upwind distance for different roughness is shown for 4.5 m measurement height in Figure 4a, and for 1.5 m measurement height in Figure 4b. For 4.5 m measurement height, peak contribution increased 1.3 times in magnitude and decreased the distance to the station by half with increased roughness. For 1.5 m measurement height, the peak doubled (from 0.01 to 0.02 % of ET).

Figure 4. Effect of roughness on the water vapor flux footprint at different measurement heights: (a) relative contribution of the upwind distance to total ET for two surface roughnesses (measurement height = 4.5 m); (b) relative contribution of the upwind distance to total ET for two surface roughnesses (measurement height = 1.5 m).
Overall, for the rough surface the measurement height had a more profound effect on the footprint than for the smooth surface, and for lower measurement height the roughness had a more profound effect on the footprint than for the higher measurement height. Therefore, for practical purposes, both measurement height and roughness should be regarded for optimal station positioning and instrument placement.

**Effect of Stability**

Effect of stability on the upwind distance contribution of latent heat flux is shown in Figure 5 (adopted from Leclerc and Thurtell, 1990). As can be seen from the figure, for the same measurement height and roughness, changes in atmospheric stability can expand the footprint several times. For a sensor height of 1.5 m and a canopy height of 0.6 m, very unstable conditions can lead to the flux footprint being mostly within 50 m of the station. In near-neutral conditions most of the footprint is located between 5 and 250 m from the station, and during very stable conditions, the area of flux contribution is located between 15 and 500 m upwind.

![Figure 5. Effect of thermal stability on the water vapor flux footprint (adapted from Leclerc and Thurtell, 1990).](image)

Important practical implications of the effect of stability on the footprint for station positioning and data processing are the following: flux data at very stable conditions may need to be corrected or discarded because of the insufficient fetch, and flux data at very unstable conditions may need to be corrected or discarded because a large portion of the flux comes from an area very close to the instrument (often disturbed by maintenance activity).

**Summary**

Contribution of the latent heat flux from the upwind distance was examined for two measurement heights on two days in the growing season of 1999. April 8, 1999, was soon after the burn; vegetation was less than 5 cm tall, and hence the roughness was low. July 30 had a fully developed canopy of 60 cm (hence, higher roughness). Both days had near-neutral thermal stability.
Comparison between these days in terms of measurement height and roughness and in terms of hypothetical changes in stability demonstrated the significant effect of measurement height, surface roughness, and thermal stability on the flux station footprint. Size of the footprint (and sufficient fetch requirement) significantly increased with increased measurement height, decreased surface roughness, and changes in thermal stability from unstable to stable. Immediate surroundings of the flux station contributed considerably to the measured flux when measurement height was low or surface roughness was high, or if conditions were very unstable. Also it was demonstrated that both fetch requirement and conditions of the surface in the immediate surroundings of the flux stations can and should be regarded for station placement, maintenance, and data quality control.

References


Station Density and Areal Coverage of Networks

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Abstract

In questions of network station density, the cost of purchasing and operating stations must be weighed against the incremental value of additional station coverage. It may be possible in some cases to design networks that fulfill the monitoring goal but do not have the same set of sensors at each station site (Ashraf et al., 1997). Questions that should be addressed are “Where within the area of the station network will the data be applied?” and “Are data to be used to integrate up to an areal average value or will the data be interpolated to non-station sites?” The required station density requirements in these two situations may be quite different. The latter case is examined in this paper. The goal is to determine the spatial characteristics of various weather variables that are measured in an automated weather data network (AWDN), first described by Hubbard et al. (1983). The relationships derived here are based on analyses of many stations over a long period of time (14 years), a luxury not available to individuals with small or recent networks. The methodology for this study involved performing regressions between two stations, then repeating the process with other surrounding stations. A data set with distance of separation vs. root mean square error (RMSE) was thus compiled. Good spatial coherence was observed for all variables except precipitation.

Spatial Analysis Methods and the Daily Data Set

Data were from 1986 to 1999 for 21 stations from a larger network (Hubbard et al., 1983). The station locations can be seen in Figure 1. The variables included in the analyses were

![Figure 1. Stations with data from 1986 to 1999, denoted by their distance (km) from Mead, Nebraska.](image-url)
daily (midnight to midnight): maximum air temperature (1.5 m), minimum air temperature (1.5 m), average relative humidity (1.5 m), average soil temperature (10 cm depth), average wind speed (3 m), total solar radiation, total precipitation, and potential evapotranspiration.

In previous work, Hubbard (1994) showed that the $r^2$ between a variable measured at a central station and the same variable measured at surrounding stations decreases with distance from the central location. The change in the relationship with season and from one variable to another was also presented.

In this paper, the decay of the extrapolation accuracy will be represented by the change in the root mean square error (RMSE) with distance from the central location. The methodology is as follows.

A regression between two stations is performed. Assuming the scatter is normally distributed around the “best fit” line, then the RMSE associated with this regression is to the best fit line as the standard deviation is to the normal curve. Thus about 68% of the points will fall within ±1 RMSE, 95% percent of the points will fall within ±2 RMSE, and more than 99% of the points will fall within ±3 RMSE of the best fit line.

Camargo and Hubbard (1999) found a close agreement between subhumid and semiarid climates in regard to these spatial variability relationships.

By repeating the regression with other surrounding stations, a data set with distance of separation vs. RMSE can be compiled. The month of July was selected to illustrate this method. July is an important month for most of the agricultural crops growing in the Midwest, and the precipitation and heat patterns can greatly influence irrigation frequency in the semiarid portions of the High Plains region.

Results for Automated Weather Stations

The RMSE extrapolated back to a distance of zero reflects in an average sense the comparability among temperature sensors. For maximum daily temperature, this intercept is about 1°C (Figure 2). The rate of increase is slow, and at a separation distance of 50 km the RMSE is of the order of 1.2°C.

For minimum temperature, the RMSE intercept was about 1°C (Figure 3). The increase in RMSE for minimum temperature is lower than for maximum temperature with an RMSE of about 2°C at 300 km, compared to nearly 3°C at 300 km for the maximum temperature.

For relative humidity (Figure 4), the intercept is 3–4%. Considering the diffi-

Figure 2. RMSE vs. distance from Mead, Nebraska, for maximum temperature.
iculty in measuring relative humidity, this seems like a reasonable expression of the sensor-to-sensor variability. The "best fit" line crosses 5% humidity at about 75 km.

For soil temperature in July (Figure 5), the increase of RMSE with distance is again gradual. The intercept value is about 1.3° C in this case and is higher than either the maximum or minimum temperature values. This indicates that the underlying surface has more variability than the air above, over short distances, but the "best fit" line is not as steep and the RMSE at 300 km is only on the order of 2° C.

For wind speed (at 3 m) the intercept is about 0.4 m/s and the RMSE increases to about 0.5 m/s at 50 m (Figure 6). In the case of wind speed, there appears to be more scatter about the "best fit" line than for the temperature variables. This indicates that the microclimate of the sites is more influential in the case of wind than for many of the other variables.

For daily solar radiation, the RMSE is about 2 MJ/m² at the intercept (Figure 7). The RMSE increases to about 3 MJ/m² at a distance of 100 km (Figure 7). It appears that there is little response to distance at that level. If there is a plateau in this region, it may be advisable to use the RMSE below about 200 km to obtain the "best fit" line.

The results for daily precipitation are shown in Figure 8. The "best fit" line is nearly flat, which suggests that the separation distances are beyond the threshold wherein a significant spatial coherence can be found. The RMSE for the nearest station is about 4 mm while prac-
tically all other stations have RMSE values in excess of 6 mm. The intercept in this case probably does not indicate the variability between co-located rain gauges.

For potential evapotranspiration the RMSE intercept was about 0.5 mm (Figure 9). This value increased to 1 mm at a distance of 100 km. The typical ETp values during July would be on the order of 8 to 10 mm. The relative error at a distance of 50 km would then be in the range of 5–10%.

**Summary and Conclusions**

For the stations presented in this study, good spatial coherence was observed for all variables except precipitation. This implies that a small number of stations of the same type in relatively even terrain and with separation distances not exceeding 200 km could yield important information relative to the accuracy of interpolation or extrapolation in the vicinity.

The intercepts derived herein were based on linear interpolation over all stations, even those with separation distances in excess of 500 km. There is evidence that a plateau exists beyond about 200 km separation. Future linear relationships may be limited to the range of 0 to 200 km.

The RMSE intercepts found were about $1^\circ$ C for maximum, minimum, and soil temperature, 4% for relative humidity, 0.4 m/s for wind speed, 2 MJ/m$^2$ for solar radiation, and 0.5 mm for potential evapotranspiration. These intercepts are most likely the residual error between sensors. There was insufficient station
density to derive the intercept for precipitation.

Although RMSE increases above the intercept values with distance of separation, it should be noted that the worst case for network accuracy would be with a single event interpolation. Any applications that require the averaging or accumulation of multiple events (average temperature, growing degree days, accumulated ETp, etc.) will likely result in some cancellation of errors. In addition, although single station pairings were used here to study the spatial structure, the effect of using multiple stations in deriving a local estimate would further reduce error since the stations represent the spatial pattern present in the data.

References
Relating Temperature Errors to Underlying Surface Characteristics

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Abstract
Both non-aspirated and aspirated radiation shields create their own microclimate and therein are the sources of temperature measurement errors. From a climatological viewpoint, it is necessary to evaluate the air temperature measurement errors caused by the underlying surface changes.

Four common air temperature radiation shields, including the ASOS, MMTS, Gill, and Cotton Region Shelter (CRS), were investigated under typical grass ground surface and different underlying surfaces (black, white, and aluminum). The shield effectiveness was evaluated by measuring the interior solar radiation and the inner surface temperatures of radiation shields. Parabolic curves describe the fraction of solar radiation entering shields, which increased as the solar reflectivity of the underlying surface increased. The rank of solar shielding effectiveness was ASOS > CRS > MMTS > Gill (i.e., total interior solar radiation loading in relative terms was ASOS : CRS : MMTS : Gill = 1:1.3:1.7:2.5) under typical grass surface conditions. The increase in interior solar radiation from the typical grass surface to the white surface went up by a factor of 1.2, 2.3, 1.6, and 1.9, respectively, for the ASOS, MMTS, Gill, and CRS shields. The ASOS shield had an obvious drawback for the infrared radiation effectiveness as a result of the heat sink associated with the chilled-mirror dew point temperature measuring system located in the middle portion of the shield. The rank of the infrared shielding effectiveness was CRS > MMTS > Gill > ASOS during daytime and Gill ≥ MMTS > CRS ≈ ASOS during nighttime.

Errors in air temperature measurement depend on the accuracy of the sensor and on successful coupling of the sensor to the air. This coupling depends on how well the shields block solar and terrestrial radiation from the sensor surface while maintaining airflow (natural or aspirated). A model is based on the energy balance of the sensor, which is affected by the interior solar radiation load caused by solar radiation penetration into the radiation shield, net infrared radiation exchange between the shield surface and sensor surface, air speed inside or outside the radiation shield, and the surface radiative properties of the sensor and the radiation shield. Air temperature measurement errors on a radiation shield were simulated. The results demonstrate that air temperature errors are inversely proportional to the ambient wind speed. Daytime air temperature errors were much larger than those during nighttime. The air temperature error ranged from +2.0°C to +4.0°C under no-wind conditions during midday under clear skies. The air temperature sensor with larger emissivity and small solar absorptivity was the best choice for daytime measurements, while an air temperature sensor with small emissivity (regardless of solar absorptivity) was preferable during nighttime. An increase or decrease of solar radiation received by the air temperature sensor could significantly change air temperature errors. At low wind speeds, the common non-aspirated radiation shield cannot provide an environment where the sensor can reach equilibrium with the air temperature.
Introduction

In taking outdoor air temperature measurements, the radiation shield cannot block all undesired solar and infrared radiation without reducing air flow in the vicinity of the air temperature sensor and thereby uncoupling the sensor from the air it is meant to measure. The four most common temperature radiation shields employed in the U.S. weather station networks are the Cotton Region Shelter (CRS), Maximum and Minimum Temperature System (MMTS), Gill, and Automated Surface Observing System (ASOS). Most studies investigating shield effects on air temperature measurement to date have shown that daytime heat loading on a sensor depends mainly on incoming global solar radiation and reflected solar radiation by the underlying surface, but the difference in air and sensor temperatures is reduced at higher ambient wind speeds (Gill, 1983; Wendland and Armstrong, 1993; Wylie and Lalas, 1992; Richardson, 1995; and Guttman and Baker, 1996). Gill (1979) pointed out that “the degree of heating in full sun is of primary importance to choice of materials, and the nocturnal radiation characteristics only secondary.” The multi-plate radiation shields (e.g., Gill shield) usually have air temperature errors of about 0.5 to 1°C (Richardson, 1995), but sometimes possibly reach nearly 5.0°C (Tanner, 1990) during the daytime. Gill (1983) conducted wind tunnel tests of several naturally ventilated radiation shields under high radiation and low wind speed conditions. An array of high output lamps was used to simulate the sun and the shield was placed over a simulated snow surface. The air temperature error varied greatly depending on wind speed and shield type, ranging from +5°C to nearly +20°C at the lowest wind speeds. In addition, when the temperatures of the sensor and the interior walls are not equal there is a net exchange of infrared radiation and the sensor temperature will no longer represent the “air” temperature. These studies found or implied that upgrades of the air temperature measurement system were responsible for shifts in the recorded air temperatures. However, the magnitude and direction of temperature shifts (or errors) among studies were not consistent. To better understand the temperature shifts, one must relate the magnitude and direction of shifts to the properties of the radiation shield and the microclimate it imposes on the air temperature sensor.

An ideal radiation shield would block all solar radiation, but this is currently impossible because openings are necessary to allow air flow through the shield. Therefore, the determination of interior solar radiation and changes of interior solar radiance caused by different underlying surface characteristics becomes necessary to evaluate the radiation shields and the errors in air temperature measurement. The specific objectives of this study are to (1) investigate the solar and infrared radiation inside the shields under typical grass surface; (2) determine solar radiation changes inside the shields when the underlying surface is artificially changed; and (3) examine the air temperature errors caused by solar radiation loading and infrared radiation loading with changing air speed inside the radiation shield.

Materials and Methods

Experimental Design and Measurements

Solar radiation inside the shields was measured during the summer of 1998 at the University of Nebraska’s Horticulture Experimental Site (40°38'N, 96°67'W, altitude 383 m)
located in Lincoln, Nebraska. The site for this study is on flat terrain with a surface of mowed grass. There are few physical obstructions within a radius of 100 m and none within 25 m. Ambient global solar radiation was measured at a distance 20 m from the radiation shields at a height of 1.5 m. The ASOS, MMTS, Gill, and CRS shields were mounted at a height of 1.5 m above the grass surface and 10 m apart. A pyranometer was mounted inside each of the four radiation shields. All solar radiation measurements were taken with LI-200S pyranometers (LI-COR, 1991) appropriately calibrated (see Lin and Hubbard, 1999; Hubbard et al., 2000). The interior space of the ASOS radiation shield is limited by the aspirator fan and hygrothermometer assembly enclosed in the ASOS system so that the LI-200S was mounted at only position of air temperature sensor height (Figure 1). The LI-200S was positioned at the heights from 25 mm to 125 mm at 20 mm intervals inside the MMTS shield, from 20 mm to 120 mm at 20 mm intervals inside the Gill shield, and from 35 mm to 535 mm at 100 mm intervals in the CRS shield. At each

![Diagram of radiation shields and pyranometer locations](image)

**Figure 1.** Sketch of LI-200S pyranometer locations inside the shields. The ASOS shield provides only one position to install the LI-200S. There are six positions available inside the MMTS, Gill, and CRS shields. Both the lowest and highest positions are labeled on each shield. The other four measurement positions are located between the lowest and highest position with equal distance. Note that the above four shields are not under the same scaling size.
height, the upward solar radiation was measured. The downward radiation was measured at four vertical heights because the LI-200S pyranometer could not be accommodated at the highest and lowest positions. During the measurements, the radiation shields and pyranometers were kept level with respect to the horizontal.

Contributions of solar radiation from underlying "artificial" surfaces were measured inside the shields with the LI-200S installed at the normal operating air temperature sensor height. An artificial ground surface was created by installing first aluminum, then black and finally white painted plywood over a rectangular area 7.32 m \times 4.88 m. The natural grass surface and the three painted plywood surfaces gave four surface treatments. Surface solar reflectivities (daily average) are 0.06, 0.24, 0.69, and 0.85 for the black, grass, aluminum, and white surfaces, respectively (Monteith and Unsworth, 1990; Lin and Hubbard, 1999). Above each surface treatment, the radiation shields were installed at 1.5 m at symmetrical positions (separation distance was 2.44 m) along the center line of the artificial surface. Incoming solar radiation (with the pyranometer installed facing upward) and outgoing solar radiation measurements (with the pyranometer inverted) were measured inside the ASOS, MMTS, Gill, and CRS shields under clear sky conditions. The data sampling rate was 5 seconds and averages were formed every 3 minutes. The duration of solar radiation measurements was from June 20 to September 30 (DOY 171 to DOY 273, 1998). The criteria for selecting the data for analyses were based on weather conditions; i.e., only cloudless daytime or mostly sunny daytime data were used to evaluate the solar radiation inside the shields. All solar radiation measurements were collected corresponding to solar time.

Infrared radiation effects on air temperature measurements were determined using the difference between the shield’s average inner surface (wall) temperature and the sensor temperature. Five fine-wire cement-on thermocouples (Type E, 1.27 mm in thickness, 9\times19 \text{mm}^2 rectangle shape) were installed on the inner surfaces of each shield located above, east, south, west, and north of the air temperature sensor to measure the inner surface temperatures of each shield. The inner surface thermocouples were in full view of the air temperature sensor inside the shield but did not cause an obstruction to air flow or solar radiation. The temperature sensors inside the shields were the hygrothermometer inside the ASOS, the thermistor inside the MMTS, the HMP35 (Campbell Scientific, Inc.) air temperature sensor inside the Gill, and the HMP35 sensor inside the CRS shield. All thermocouples were calibrated using a dry-well temperature calibrator, Model D55SE (AMETEK Inc., JOFRA Instruments) with \pm0.3\degree C accuracy. Shield temperatures were measured from January 1997 to October 1997 at the experimental site. The inner surface thermocouples were recalibrated once during the measurement period. The sampling rate for the inner surface temperature and the air temperature sensor measurements was 30 minutes.

**Data Analysis**

The relative magnitude of incoming solar radiation inside each shield is evaluated relative to the incoming solar radiation ratio (ISRR\%), defined as:

\[
\text{ISRR}\% = \frac{\text{ Incoming solar radiation inside shield}}{\text{Incoming global solar radiation outside shield}} \times 100. \quad (1)
\]
The numerator on the right-hand side of Eq. 1 is the incoming solar radiation inside the shield measured when the LI-200S is mounted facing upward. Likewise, the outgoing solar radiation ratio (OSRR%) is defined the same as (1), except the numerator of the right-hand side of (1) is the outgoing solar radiation inside the shield (i.e., when the LI-200S is mounted facing downward).

Total solar radiation loading can be calculated by combining the contributions of ISRR% and OSRR% as:

\[ TSRR\% = 0.5(ISRR\% + OSRR\%) \]  

(2)

"Averages" of ISRR%, OSRR%, and TSRR% were calculated as the mean ratio over all heights for each given time and shield. "Daily" ISRR%, OSRR%, and TSRR% were defined as the mean ratio over the day at a specific height. The average ISRR%, OSRR%, and TSRR% for the radiation shields were expressed as nonlinear (parabolic) functions of solar time during daylight hours of the general form:

\[ \text{Ratio}\% = a + bt^2 \]  

(3)

Mathematically, Eq. 3 represents a standard parabolic curve, where Ratio% refers to ISRR%, OSRR%, or TSRR%, and \( t \) represents the solar time (a shift of 12 hours is used so that at solar noon the equation reaches a minimum or maximum, i.e., \( t = \text{solartime} - 12 \)). The parameter \( a \) represents the minimum Ratio% incident on the air temperature sensor inside the ASOS, Gill, MMTS, and CRS shields. The parameter \( b \) in Eq. 3 denotes the degree of openness of the parabola. As \( b \) becomes smaller the parabola becomes more open and is flat when \( b = 0 \). Therefore, the integration area of parabolic curve was taken as an indication of solar shielding effectiveness for each radiation.

The five inner surface temperatures were simply averaged to represent the shield inner surface temperature. The inner surface temperature data for 85 days were taken from DOY 15 to DOY 39, from DOY 121 to 157, and from DOY 210 to 232, 1997. The difference between the average inner surface temperature and the sensor temperature is used to evaluate the infrared shielding effectiveness for each radiation shield.

**Radiation Loading Model**

Radiation energy of the air temperature sensor inside the shield for both net infrared radiation loading (\( IR_{load} \)) and absorbed solar radiation loading (\( SR_{load} \)) must be equal to convection heat loss from the sensor surface. Therefore, the appropriate energy balance for the air temperature sensor, at steady state condition while ignoring conduction heat, is

\[ \frac{J_1 - E_{bl}}{A_1R_1} + a_S SR_{load} = HA_1(T_{air} - T_1) \]  

(4)

where \( J_1 \) represents the radiosity of air temperature sensor; \( E_{bl} \) is black body emissive power of air temperature sensor surface; \( A_1 \) is the surface area of the sensor; \( R_1 \) represents the energy flow resistance of the sensor; \( a_S \) is the solar absorptivity of the temperature sensor (with 0.3 as a typical value); \( H \) is convection heat coefficient (W m\(^{-2}\) K\(^{-1}\)) of the
sensor; and $T_{air}$ and $T_i$ represent the temperatures of air and temperature sensor. If both the $IR_{load}$ and $SR_{load}$ are zero and the temperature sensor is “wire less” and “supportless” (i.e., no conductive heat through temperature sensor body), the radiation shield design has perfect shielding effectiveness and the air temperature is independent of convection heat transfer coefficient ($H$).

Eq. 4 can be solved for an air temperature sensor reading $T_i$ to evaluate typical air temperature errors (i.e., difference between sensor temperature [$T_s$] and air temperature [$T_{air}$]) for both daytime and nighttime conditions. This process reveals the role played by solar radiation, infrared radiation, air speed inside the shield, and the radiative emissivities of the sensor and the radiation shield in determining the magnitude of temperature errors. The computation of the $SR_{load}$, $IR_{load}$ and convection heat coefficient ($H$) in Eq. 4 were described in detail in Lin and Hubbard (1999) and Lin et al. (2000).

**Results**

**The Solar Radiation Environment Inside the Shields**

The incoming solar radiation inside the radiation shield was measured on six nearly consecutive clear sky days, with each day used to collect data from a different height within the shield. Day of year (DOY) 183, 184, 185, 179, 181, and 182 in 1998 correspond to the six heights inside each shield. The solar radiation was measured with a downward-pointing pyranometer inside the shield on four clear days, with data collected from a different height within the shield on each day. DOY 208, 230, 220, and 229 in 1998 correspond to four heights. The regression coefficients of Eq. 3 for the average $ISRR\%$, $OSRR\%$, and $TSRR\%$ inside each radiation shield are listed in Table 1. The trend in the average $TSRR\%$ inside the shields followed the sum of average $ISRR\%$ and average $OSRR\%$ (Figure 2). The ASOS shield presented a relative flat curve, which is independent of the solar elevation angle owing to the fact that the ASOS shield has solid walls and only the bottom is open toward the ground surface (covered by a metal mesh). The solar radiation ratios of the MMTS, Gill, and CRS shields decreased with the increase of the solar elevation angle. Based on the integration areas, the $TSRR\%$ (Table 1 and Figure 2) had the following relative magnitudes: ASOS : MMTS : Gill : CRS = 1:1.7:2.5:1.3 (45.5:77.0:115.9:68.6).

**Table 1. The regression coefficients of Eq. 3 for the $ISRR\%$, $OSRR\%$, and $TSRR\%$ inside each radiation shield. The $r^2$ represents the regression coefficient of determination.**

<table>
<thead>
<tr>
<th>Shields</th>
<th>$ISRR%$</th>
<th>$OSRR%$</th>
<th>$TSRR%$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a$</td>
<td>$b$</td>
<td>$r^2$</td>
</tr>
<tr>
<td>ASOS</td>
<td>0.152</td>
<td>-0.0047</td>
<td>0.72</td>
</tr>
<tr>
<td>MMTS</td>
<td>5.136</td>
<td>0.186</td>
<td>0.95</td>
</tr>
<tr>
<td>Gill</td>
<td>6.562</td>
<td>0.205</td>
<td>0.96</td>
</tr>
<tr>
<td>CRS</td>
<td>4.178</td>
<td>0.0092</td>
<td>0.92</td>
</tr>
</tbody>
</table>

98
Figure 2. Average TSRR% for the ASOS, MMTS, Gill, and CRS shields. The integration area of each curve from solar time 6:00 to 18:00 is 45.5, 77.0, 115.9, and 68.6, respectively, for the ASOS, MMTS, Gill, and CRS shields.

Solar Radiation Inside the Shields over Various Surfaces
Increasing the solar reflectivity from a black to a white surface for the ASOS had little effect on the daily ISRR% because of the solid barrier represented by the ASOS structure and the black painted inner surface (Figure 3a). The daily ISRR% inside the Gill, MMTS, and CRS had almost the same linear increasing rate with the increase of surface solar reflectivity. The daily OSRR% trends inside the shields were different from that of the ISRR% (Figure 3b). The OSRR% for the ASOS increased as the reflectivity changed from the black to the grass surface and remained almost constant (around 7.5%) for surface solar reflectivity of 0.25 and above. This result is attributed to the fact that the black inner surface of the ASOS shield absorbs the reflected solar radiation from the ground surface. The daily OSRR% of the CRS and MMTS increased more rapidly than the daily OSRR% of the Gill shield. Increasing rates of daily TSRR% for the shields from the typical grass surface to the white surface were 1.6, 2.3, 1.9, and 1.2, respectively, for the Gill, MMTS, CRS, and ASOS shields (Figure 3c). Therefore, we anticipate that a snow-covered ground surface (with a surface reflectivity of about 0.85) will increase the interior solar radiation for the Gill by 1.6 times, the MMTS by 2.3 times, and the CRS by 1.9 times, which would act to decouple the temperature sensor from the air temperature. The rank of solar radiation shielding effectiveness, for the whole range of surface solar reflectivity, was ASOS > CRS ≥ MMTS > Gill.

The daily TSRR% inside the CRS and MMTS shields was nearly the same, indicating similar shielding efficiency. The Gill shield had larger values, especially at the lower ground surface solar reflectivity. We attribute the high solar radiation shielding efficiency of the ASOS to the solid sides of the shield.
Figure 3. (a) Daily ISRR%, (b) daily OSRR%, and (c) daily TSRR% changes with changes of underlying surface solar reflectivity.
Temperature Difference between Shield Inner Surface and Sensor Temperatures

The difference between the average daytime inner wall surface temperature and the average temperature of the sensor varied from -3°C to +4°C (Figure 4). The shape of temperature difference distribution of each shield is Gaussian, with the modes around -0.5°C, -0.2°C, 0°C, and 1°C, and the average values -0.55°C, -0.26°C, +0.01°C, and +0.88°C, respectively, for the Gill, MMTS, CRS, and ASOS shields. The negative average temperature difference for the Gill and MMTS shields is a contradiction to previous research, in which the radiation shields were said to heat the air or air temperature sensor, resulting in a shield heating error (e.g., Richardson [1995] and Tanner et al. [1996]). Based on the absolute average difference between the shield inner surface temperature and sensor temperature (Figure 4), the infrared shielding effectiveness for each shield during daytime was ranked as CRS > MMTS > Gill > ASOS.

Figure 4. Temperature differences between the average inner surface temperature of shield and sensor temperature inside the shield during (a) daytime (upper panel) and (b) nighttime (lower panel). The total data numbers for daytime and nighttime are 2025 and 2053 taken from DOY 15 to DOY 39, from DOY 121 to DOY 157, and from DOY 210 to DOY 232, 1997.

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During nighttime, the distribution modes for the difference between the inner surface temperature of radiation shield and the sensor temperature were approximately zero (Figure 8). The average values were negative, with -0.20, -0.20, -0.12, and -0.07°C, respectively, for the ASOS, CRS, MMTS, and Gill shields. For the MMTS and Gill shields, there were no systematic temperature differences between the inner surface of the radiation shield and the air temperature sensor, as evidenced by the symmetrical shapes of the distributions. The only exception is at a difference of +1°C. The physical basis for this small departure from symmetry has not been determined. The distributions for both ASOS and CRS shields are slightly skewed toward the cooling effects.

**Daytime and Nighttime Air Temperature Errors**

Simulated daytime errors from the model with a known emissivity (0.9) of the shield inner surfaces are shown in Figure 5. As the air temperature sensor emissivity decreases, the errors increase, especially for a low convection heat coefficient ($H = 5$ W m$^{-2}$ K$^{-1}$). The

![Diagram](image)

**Figure 5.** (a) Simulated daytime air temperature error under different sensor emissivities at solar time 10:00. (b) Simulated air daytime temperature error for different shield inner surface temperatures when both inner surface and sensor surface emissivities are 0.9 and $H = 30$ W m$^{-2}$ K$^{-1}$. The X axis of (a) represents the convection heat coefficient and corresponding ambient wind speed outside the shield at the same height as the radiation shield.
Figure 6. Simulated nighttime air temperature error under different sensor emissivities at solar time 0:00 with (a) 1°C temperature difference and (b) 3°C temperature difference between the shield inner surface temperature and air temperature. The X axis presents the convection heat coefficients and corresponding ambient wind speed values outside the shield at the same height as the radiation shield.

Maximum errors ranged from +1.9 to ±3.9°C, depending on the sensor emissivity. When H was greater than 45 W m⁻² K⁻¹ (corresponding to 0.7 m s⁻¹ air speed inside or 2.4 m s⁻¹ outside the shield [see Lin et al., 2000]), the temperature error was no longer sensitive to the emissivity of the air temperature sensor; all errors were less than ±0.5°C. When H reached 85 W m⁻² K⁻¹, the air temperature error was around +0.25°C.

For a +1.0°C temperature difference between the shield inner surface and air temperature, the solar and infrared radiation heating error was inversely proportional to the ambient wind speed (Figure 5a). The maximum error reached almost +4°C when the emissivity of the temperature sensor was 0.05. When H approached 45 W m⁻² K⁻¹, air temperature errors were less than +0.5°C. Combining the solar radiation and the infrared radiation
Figure 7. Simulated nighttime air temperature error for different inner surface temperatures of the radiation shield when both sensor and shield inner surface emissivities are 0.9.

effects (shield inner surface temperature and sensor emissivity) for an entire day, a +5°C difference between the shield inner surface temperatures \( T_{air} +5 \) in Figure 5b) and air temperature may result in an error as high as 1.4°C during the day. However, with a -5°C difference between the shield inner surface temperature and air temperature, the temperature error could be greater than -0.5°C during the day. In this situation, each two-degree increment of temperature difference between shield inner surface temperature and air temperature caused a 0.32°C increment of temperature errors.

Nighttime air temperature radiative error is affected only by infrared radiation. Simulations revealed that errors due to heating or cooling of the sensor (shield temperature > \( T_{air} \) or shield temperature < \( T_{air} \)) were inversely proportional to the ambient wind speed (Figure 6). When the emissivity of the temperature sensor was 0.05, the maximum temperature error could reach ±0.5°C and ±1.5°C under the conditions of a ±1°C and ±3°C temperature difference between the shield inner surface temperature and air temperatures. Increasing the temperature sensor emissivity decreased the air temperature error.

Simulations showed that as the shield inner surface temperature departed further from the actual air temperature, the air temperature error increased (Figure 7). When the shield inner surface temperature was lower or higher than the ambient air temperature at a convection heat coefficient \( (H) \) of 30 W m\(^{-2}\) K\(^{-1}\), a temperature error of about +0.7°C to -0.7°C (Figure 7) could result. For this situation, each two-degree change in the shield inner surface causes a ±0.27°C change in air temperature error.

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Without considering the infrared effects ($T_{air} =$ shield temperature), the change in air temperature errors was nearly linear with changes in solar radiation loading (Figure 8). The maximum air temperature errors were +3.7°C, +1.9°C, and +1.1°C under three conditions indicated in Figure 8.

![Graph showing air temperature errors versus convective heat coefficient](image)

**Figure 8.** Simulated daytime air temperature errors caused by increase (double) or decrease (half) of interior solar radiation loading at solar time 10:00 under conditions of temperature sensor emissivity = 0.9 and the solar absorptivity of temperature sensor = 0.3.

**Discussion and Conclusions**

Solar radiation in the interior of the radiation shield is an important quantity affecting air temperature measurement. Parabolic curves were fit to the fraction of solar radiation entering radiation shields as a function of time of day (Figure 2). Although the total solar radiation ratio (TSRR%) values were small during midday from solar time 10:00 to 14:00, the solar radiation loading on an air temperature sensor installed inside the shield can be relatively large under clear sky conditions since the absolute interior solar radiation results from multiplication of the TSRR% and incoming global radiation. Compared to the non-aspirated radiation shields (Gill, MMTS, and CRS), the ASOS shield provided better solar radiation shielding because of its closed cylindrical structure and a relatively large cap (dome) above the shield (Figure 1). The average TSRR% values inside the shields suggested that the solar radiation shielding effectiveness had the following order: ASOS > CRS > MMTS > Gill.
Although the ASOS is a bottom-open and side-closed shield, the small interior space and black inner surface of the ASOS effectively made it function as a quasi-blackbody. The absorbed radiation energy can be partly or completely dissipated by its aspirated air flow. The ASOS performed efficiently as a solar radiation shield above all types of ground surfaces. In addition, the solar radiation shielding effectiveness for the ASOS remained nearly constant from the typical grass surface to the white surface (Figure 3c). According to the LI-200S measurements, the daily TSRR% inside the Gill was larger than that in the CRS and MMTS shields over all types of underlying surfaces. The increase in interior solar radiation from the typical grass surface to the white surface went up by a factor of 1.2, 2.3, 1.6, and 1.9, respectively, for the ASOS, MMTS, Gill, and CRS shields.

In contrast to solar radiation effectiveness, the ASOS performed the worst of the four radiation shields tested for infrared radiation effectiveness during daytime and nighttime conditions. The ASOS design allows the air to flow through from the air temperature sensor (bottom portion inside) to the chilled mirror device and past the relatively large heat sink (middle portion inside). The net infrared radiation on the air temperature sensor may heat or cool the air temperature sensor, depending on the difference between the inner surface wall temperature and the ASOS sensor temperature and other factors, including ambient solar radiation and dew point temperature depression. The chilled mirror system in the ASOS shield is a potential drawback for the ASOS air temperature measurement. Statistical distribution of the net infrared radiation loading inside the CRS shield was centered on zero for both daytime and nighttime conditions but averaged -0.2°C temperature difference for nighttime. The Gill and MMTS shields were most likely to cause an infrared radiation deficit for the sensor during daytime. According to the heat transfer considerations, heating or cooling effects are not only dependent on the surface temperatures but also on surface emissivities. Therefore, the surface with a low temperature certainly does not transfer the heat onto the surface with high temperature. However, the infrared radiation effect on the sensor temperatures for the MMTS and Gill shields during daytime was to slightly lower the sensor temperature, assuming the inner surface and sensor emissivities are the same. The slight cooling effects would cancel out part of the solar radiation heating effects inside the MMTS and Gill shields. There were no obvious temperature difference trends toward positive or negative for the MMTS and Gill shields during nighttime (Figure 4). The rank of the infrared shielding effectiveness was CRS > MMTS > Gill > ASOS during daytime and Gill ≥ MMTS > CRS ≈ ASOS during nighttime, based on the absolute magnitude of average temperature difference values for each shield. Tanner et al. (1996) agreed that the shields had cooling effects during nighttime but their results (Figure 8 in Tanner et al. 1996) did not exclusively support their views because the observed distribution of temperature errors was centered on zero for the Gill shield during nighttime. However, this was consistent with our simulated results (Figure 6).

Simulations of air temperature error due to radiation shield effects revealed that daytime air temperature error typically increased when the temperature of the inner surface of the shields was higher than the air temperature. A larger convection heat transfer inside the shield reduces the air temperature error affected by the air temperature sensor emissivity. This is because a larger convection heat rate can dominate the heat (energy) transfer process compared to solar radiation loading term \( a_g S_{load} \) and infrared radiation loading...
term \((R_{rad})\). The daytime air temperature errors caused by solar radiation heating were inversely proportional to the ambient wind speed inside the shield. An increase of air temperature sensor emissivity decreased the air temperature errors during daytime (Figure 5a). When the convection coefficient \((H)\) reached 125 W m\(^2\) K\(^{-1}\), the air temperature error was around +0.2°C. Since a large ambient wind speed (>17 m s\(^{-1}\)) is required to reach \(H = 125\) W m\(^2\) K\(^{-1}\), it can be concluded that temperature errors of at least +0.2°C are usually present under solar radiation loading during the middle of the day under clear sky conditions (Figure 5). Therefore, the simulation suggests that the common non-aspirated radiation shield is unable to provide an equilibrium air environment sensed by the air temperature sensor. So, appropriate increase in air flow inside the shield is necessary to improve the accuracy of air temperature measurement.

Many previous researchers (Fuchs and Tanner, 1965; McTaggart-Cowan and McKay, 1976; McKay and McTaggart-Cowan, 1977) have shown that the radiation shield temperature can become lower than the ambient temperature during nighttime. Nighttime air temperature errors changed by about 0.27°C for each 2°C change in the difference between the shield and sensor temperature but were centered on zero in the absence of solar radiation. Increasing the emissivity of an air temperature sensor had the opposite effect on nighttime temperature errors compared to daytime errors (Figures 5a and 6). Nighttime air temperature errors were smaller in magnitude than daytime air temperature errors. Generally, the temperature errors were positive during the daytime (Figure 5). However, the errors could be either negative or positive during nighttime, depending on the difference between the radiation shield inner surface temperature and the air temperature, and could decrease with an increase of ambient wind speed (Tanner et al., 1996). Therefore, we conclude that a larger sensor emissivity with a lower solar absorptivity is preferred overall because the errors in nighttime air temperature will be relatively small.

The simulated air temperature errors could be substantial under the conditions of maximum interior solar radiation from solar time 10:00 to 14:00 inside the MMTS, Gill, and CRS shields and no ambient wind speed (the convection coefficient is minimum) when the underlying surface is fresh snow (see Figure 3c). Even at more than 7.5 m s\(^{-1}\) ambient wind speed, the air temperature errors additively caused by solar radiation effects are comparable to the errors given by the manufacturers (around 0.3 °C) in this case.

**Acknowledgments**

We are grateful to Vickie L. Nadolski (NWS) and Tom Blackburn (NWS) for the loan of two ASOS and two MMTS temperature systems. We also would like to thank Drs. E.A. Walter-Shea, J.R. Brandle, and G.E. Meyer for valuable discussion and suggestions on our experiments.

**References**


Maintenance, Quality Assurance, and Network Management Issues
Standard Meteorological Measurements

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Abstract
Advances in the design of sensors are making it possible to collect increasing numbers of observations on a variety of scales, and at relatively low cost. For agricultural applications, the most common measurements are air temperature, air pressure, relative humidity and dewpoint temperature, cloud ceiling height, solar radiation, precipitation, and wind speed and direction. Selecting sensors to perform these measurements involves consideration of the tools' various advantages and disadvantages for specific applications. This chapter provides a discussion of the accuracy and stability, ease of maintenance, and comparative cost of various types of the sensors most often used in agricultural applications. The importance of preventive and periodic sensor testing is also stressed.

Introduction
People have invented and tested devices that measure atmospheric variables since the time of Leonardo de Vinci. In recent years, the miniaturization of circuits and sensors has made it possible to collect ever-increasing numbers of observations on scales not previously considered. In the field of agricultural meteorology, the physical principals are basically the same as for any other branch of meteorology. In agricultural applications, the primary portion of the atmosphere that is of interest is the lower planetary boundary layer, and the interesting problems often require an understanding of the interactions between the atmosphere, the plant communities, and the soils.

Temperature and pressure are of interest because of their role in energy exchange and air movement. Temperature is perhaps of greater interest in agricultural applications because it is one of the variables that indicates whether a particular microclimate is suitable for the growth and development of an organism. Wind speed is of interest because of its role in convective energy exchange and also increasingly because the winds determine the movement of odors, sprays, and other chemicals as they drift in the atmosphere.

Recent innovations in satellite monitoring, doppler radar, lightning detection, and Automated Surface Observing Systems (ASOS) have provided new nationwide data sets. State and regional automated weather station (AWS) networks have also developed in the past few decades (Meyer and Hubbard, 1992).

The automated weather stations accurately measure and record standard meteorological variables and can form networks over large areas, at relatively low cost (Tanner, 1990). The new AWS data makes it possible for agricultural producers to apply new tools in decision making, including crop modeling, climate change modeling, and livestock and

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forestry management. We will review the progress and status of the common measurements taken in support of agricultural operations.

**Meteorological Sensors**

The characteristic that all meteorological sensors have in common is that a property of the sensor changes in a known and predictable fashion as changes occur in an atmospheric variable of interest. This tendency for the sensor to act as an analog to the atmospheric variable is at the heart of sensor performance. In modern sensors, the property of the sensor will be continuously or regularly monitored. These properties might be (1) resistance or capacitance (e.g., resistance temperature sensor, capacitive relative humidity sensor, and capacitive barometric pressure sensor), (2) analog voltage or current (e.g., thermal pyranometer, wind direction vane, and photodiode pyranometer), (3) pulsing or switching (e.g., cup anemometer and tipping rain gauge), and (4) digital output in the new intelligent sensors (usually microprocessor-based, e.g., cloud height sensor system). The performance of a sensor system should be judged according to how well it rates in the following (Hauptmann, 1993):

- adequate sensitivity;
- high degree of accuracy and good reproducibility;
- high degree of linearity;
- good dynamic range;
- insensitivity to interface and environmental influences;
- high degree of stability and reliability;
- long life expectancy and problem-free replacement.

**Air Temperature**

Temperature sensors commonly used for measuring air temperature are platinum resistance temperature detector (PRTD), thermistors, and thermocouples. The PRTD sensing element is usually a coil of fine wire or a metal film that is constructed of platinum. The general relation between the resistance of PRTD and temperature is

\[ R = R_0 (1 + AT + BT^2 + C(T - 100)T^3) \]

where \( R \) is resistance (ohms) of the PRTD at the temperature \( T \) (°C) and \( R_0 \) is the nominal resistance of the PRTD at 0°C (e.g., typical values are 100, 200, or 1000 ohms). The constants \( A, B, \) and \( C \) are calibration coefficients from manufacturers (e.g., typical values of PRTD probe are \( A = 3.9596 \times 10^{-3}, B = -5.8488 \times 10^{-7}, \) and \( C = -5.812 \times 10^{-12} \)). For AWS applications, the temperature measuring range is relatively narrow, from -50°C to +50°C, so that the coefficient \( C \) may be ignored. The PRTD sensor is widely used in current air temperature systems, including the ASOS temperature sensor, R. M. Young temperature sensor, and Vaisala HMP45C sensor.

Like the PRTD, the thermistor is also widely used in air temperature measurements at the AWS. Thermistors are generally composed of semiconductor materials. Although positive temperature coefficient units are available, most thermistors have a negative tem-
temperature coefficient—that is, their resistance decreases with increasing temperature. An individual thermistor can be very closely approximated through use of the Steinhart-Hart equation (Steinhart and Hart, 1968):

\[ \frac{1}{T} = A + B \ln R + C(\ln R)^3 \]

where \( A, B, \) and \( C \) are curve-fitting constants. \( T \) is a temperature with Kelvin degree (°K) and \( R \) is resistance (ohms) of the thermistor at temperature \( T \) (°K). Thermistor sensors are used in the MMTS temperature sensor, Campbell 107 temperature sensor, and Vaisala HMP35C air temperature sensor.

Although the thermocouple is rarely used in AWS, it is a common type of temperature sensor. Any pair of thermoelectrically dissimilar wires can be used as a thermocouple. The wires need only be joined together at one end (measuring junction) and connected to a voltage-measuring instrument at the other end (reference junction) to form a usable system. Whenever the measuring junction is at a different temperature from that of the reference junction, a Seebeck voltage (electromotive force [EMF]) will develop that is related to the temperature difference between the two junctions. There are several common types of thermocouples, such as Type E [Nickel-Chromium (+) versus Constantan (-)], Type J [Iron (+) versus Constantan (-)], Type K [Nickel-Chromium (+) versus Nickel (-)], and Type T [Copper (+) versus Constantan (-)]. The voltage-to-temperature conversion relation is

\[ T = a_0 + a_1x + a_2x^2 + a_3x^3 + \ldots + a_nx^n \]

where \( T \) is the temperature and \( x \) is the thermocouple voltage. The \( a_1, a_2, \ldots, \) and \( a_n \) are polynomial coefficients unique to each thermocouple type. The maximum order of the polynomial (\( n \)) depends on the measuring temperature range and thermocouple type.

In the measurement of air temperature, it is necessary to convert the sensor output into a temperature reading. For the PRTD and thermistor sensors, the half bridge or full bridge circuitry is commonly selected for the signal conditioning. The constant current excitation for the bridge circuit is better than the constant voltage excitation for the resistance measurements. It is best if the output voltage is measured twice: once with current in one direction and again with the current in the opposite direction. Taking the average of the two readings in this approach causes cancellation of errors associated with excitation, voltage offsets, and electromotive force (EMF). The thermocouple voltage measurement is very straightforward, but both magnitude and sensitivity of the output signal from the thermocouple are relatively small. The signal conditioning circuitry design must provide an accurate reference junction (cold junction) temperature measurement or compensation by hardware circuits. Some data loggers include an internal thermistor or PRTD temperature sensor below the input terminals that can serve as a reference temperature for thermocouple temperature measurement. Therefore, maintaining uniform temperature at the input terminals of this type of data logger is helpful for accurate measurements.

The errors of air temperature measurements include the sensor error, data logger errors, and incomplete coupling errors. For the resistance measurements of air temperature, the stability of excitation source, extension lead (thermal conduction and lead resistance),
sensor self-heating, and extra EMF from improper wire connections are major error sources. The errors caused by sensor and data logger uncertainties are usually less than ± 0.5°C. However, it is important to remember that temperature sensors always measure the temperature of the sensor. Only under the thermal equilibrium (complete coupling between air temperature sensor and atmosphere) does the sensor temperature represent air temperature. Air temperature measurements usually involve a radiation shield. The shield blocks solar radiation and hopefully minimizes the infrared radiation effects on air temperature measurements while not interfering with ventilation. The aspirated radiation shield is able to reduce the errors caused by solar radiation, infrared radiation, and wind speed effects, but it requires more power consumption at the site. The errors caused by incomplete coupling with atmosphere for a non-aspirated shield can reach up to 2–4°C at zero wind speed and fresh snow underlying the surface, and high global solar radiation conditions (Marshall and Woodward, 1985; Tanner, 1990; and Lin, 1999). Some specifications that should be considered when using the above temperature sensors are listed in Table 1.

Table 1. The typical characteristics of temperature sensors.

<table>
<thead>
<tr>
<th></th>
<th>PRTD</th>
<th>Thermistor</th>
<th>Thermocouple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>0.4 ohms °C⁻¹</td>
<td>0.1–1.5 k ohms °C⁻¹</td>
<td>0.04–0.06 mv °C⁻¹</td>
</tr>
<tr>
<td>Stability</td>
<td>Excellent</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Linearity</td>
<td>Slightly nonlinear</td>
<td>Very nonlinear</td>
<td>Slightly nonlinear</td>
</tr>
<tr>
<td>Response time</td>
<td>10 seconds</td>
<td>5 seconds</td>
<td>Less than 5 seconds</td>
</tr>
<tr>
<td>Calibration interval</td>
<td>1 year</td>
<td>1 year</td>
<td>Less than 1 year</td>
</tr>
<tr>
<td>Excitation</td>
<td>Required</td>
<td>Required</td>
<td>No</td>
</tr>
<tr>
<td>Temperature reference</td>
<td>No</td>
<td>No</td>
<td>Required</td>
</tr>
<tr>
<td>Signal conditioning</td>
<td>Moderate</td>
<td>Easy</td>
<td>Moderate</td>
</tr>
<tr>
<td>Cost</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Advantages</td>
<td>High stability; robustness</td>
<td>High sensitivity; ease of signal conditioning</td>
<td>Low cost Fast response time</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Relatively high cost; lead wire effects</td>
<td>Nonlinear; exchangeability errors</td>
<td>Many possible sources of error; need for reference</td>
</tr>
</tbody>
</table>

Calibration of air temperature sensors should be conducted using National Institute of Standards (NIST) traceable standard thermometers, standard temperature baths, or NIST traceable dry-well calibrators. The calibration can be a source of error if improper calibration equipment is used.

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Air Pressure

Most pressure sensors today do not use the old-fashioned "fluid barometer" principle, where the height of a column of liquid is measured as an indicator of pressure. Instead, aneroid barometers with capacitive sensing mechanisms are employed to realize pressure sensors in the atmosphere applications. Although this mechanism is inherently nonlinear (since the capacitance is inversely proportional to gap width), the near-zero temperature coefficient of the capacitive sensing mechanism is very attractive. The heart of the metal capacitive pressure sensor is the capacitive cell. The capacitive cell consists of two cell halves, each with a fixed capacitor plate, a flexible center diaphragm that senses the pressure variations, and two isolating diaphragms that are backfilled with oil to the sensing diaphragm. Similarly, the silicon capacitive pressure sensor has the same basic design as the metal sensor. The capacity of sensor (C) is a function of the distance between plates (d), area of plates (A), and dielectric constant of the insulating material (K). The capacity can be calculated as follows:

\[ C = \frac{KA}{4\pi d} \]

Several typical capacitive pressure sensors are used in the weather stations, such as Vaisala PBT101B (silicon type) at the AWS and Setra Model 470 (metal type; Setra Systems Co.) at the ASOS networks. Both are called barometric pressure sensors. The barometric pressure refers to the actual pressure sensor value. The accuracy of barometric pressure sensors is strongly associated with linearity (Lin), hysteresis (Hyst), repeatability (Rep), offset temperature coefficient (offset TC), and span temperature coefficient (span TC). The total accuracy is the root-sum-square (RSS) of each error (Tandeske, 1991):

\[ \text{RSS Error} = \pm \sqrt{(\text{Lin})^2 + (\text{Hyst})^2 + (\text{Rep})^2 + (\text{Offset TC})^2 + (\text{Span TC})^2} \]

Each error usually is expressed in terms of percent of full-scale range (FS)—e.g., 0.2% FS under certain temperature ranges. The capacitive pressure sensor has a good temperature coefficient compared to piezoresistive or piezoelectric pressure sensors. The thermal effect is an important consideration in the selection of barometric pressure sensors.

Field calibration of barometric pressure sensors usually is undertaken by comparing them to more accurate barometers such as Paroscientific model 760 (Paroscientific, Inc.), which is a portable pressure standard with NIST traceability. Many pressure units are widely used today. Some unit conversion factors relative to the SI unit, the Pascal (Pa), are listed in Table 2.

Air Relative Humidity (RH) and Dewpoint Temperature

There are many air humidity and dewpoint temperature sensors for measuring the water vapor content of air. The traditional psychrometers that measure wet-bulb depression and estimate specific humidity through the psychrometric equation are gradually and commonly displaced by the hygroscopic (capacitance or resistance in changes) sensors (e.g., Vaisala humicap sensor) and condensation dewpoint hygrometers (EG & G Inc.) because
Table 2. Pressure conversion factors relative to the SI unit, the Pascal (Pa).

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversion to Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 A (atmosphere)</td>
<td>1.01325×10^5 Pa</td>
</tr>
<tr>
<td>1 b (bar)</td>
<td>10^4 Pa</td>
</tr>
<tr>
<td>1 mb (millibar) = hPa (hectoPa)</td>
<td>100 Pa</td>
</tr>
<tr>
<td>1 Mb (microbar)</td>
<td>0.1 Pa</td>
</tr>
<tr>
<td>1 inH2O (inch of water [4°C])</td>
<td>249.08 Pa</td>
</tr>
<tr>
<td>1 mH2O (meter of water [4°C])</td>
<td>9806.6 Pa</td>
</tr>
<tr>
<td>1 inHg (inch of mercury [0°C])</td>
<td>3,386.4 Pa</td>
</tr>
<tr>
<td>1 mmHg (millimeter of mercury [0°C])</td>
<td>133.32 Pa</td>
</tr>
<tr>
<td>1 MPa (mega pascal)</td>
<td>10^6 Pa</td>
</tr>
<tr>
<td>1 PSI (pounds per square inch)</td>
<td>6894.76 Pa</td>
</tr>
<tr>
<td>1 Nm² (newtons per square meter)</td>
<td>1 Pa</td>
</tr>
</tbody>
</table>

of the need for automatic measurements at the weather stations. In general, the capacitive humidity sensors are more accurate than the sensors based on resistance changes. Since the Vaisala capacitive polymer sensor became available in 1973, this type of sensor for air relative humidity measurement has become a standard in operational atmospheric humidity measurements. The major attractions of the humicap sensor are small size, small temperature dependence, and rapid response to changes in humidity. Recently the long-term stability and sensitivity at high RH values has been improved for humicap sensors. However, the small hysteresis and temperature dependency are still important parameters to characterize capacitive humidity sensors. Oscillation methods in signal conditioning circuitry are commonly selected to measure the capacitance by switching the charge or discharge of the capacitive sensor. Sensors come from the manufacturer with output directly proportional to relative humidity.

A dewpoint temperature sensor using a chilled mirror method is also called the condensation point sensor. By definition, the dewpoint of a sample of air is the temperature at which the water vapor in the air condenses. In the chilled mirror method, a mirror is cooled to the point where a fine film of condensate is present on the mirror’s surface. The temperature of the mirror at this point is equal to the dewpoint temperature. The presence of condensation is detected by the optical reflection. The dewpoint temperature is measured by a temperature sensor (usually a precision PRTD or thermistor) embedded below the chilled mirror. The sensor system is generally housed in an aspirated shield and requires periodic cleaning of the mirror surface and checks of calibration adjustments; with reasonable maintenance, absolute accuracies of ± 0.5°C are attainable.

Some applications require the dewpoint temperature or saturation vapor pressure data rather than air relative humidity data from the AWS networks. In this case, there are two
methods for calculating the dewpoint temperature \( [T_d(^\circC)] \) using air temperature \( [T(^\circC)] \) and relative humidity (RH) sensors. The calculation algorithm of dewpoint temperature \( (T_d) \) from the Magnus-Tetens formula (Barenbrug, 1974) is

\[
T_d = \frac{b \cdot \alpha(T, RH)}{a - \alpha(T, RH)}
\]

\[
\alpha(T, RH) = \frac{a \cdot T}{a + T} + \ln(RH)
\]

where \( a = 17.27 \) and \( b = 237.7 \) (°C). The calculated dewpoint temperature ranges from 0 to 50°C under the limits of air temperature (0°C < \( T < 60\)°C) and relative humidity (0.01 < RH < 1.0). The uncertainty of calculated dewpoint temperature is ±0.4°C under conditions of air temperature uncertainty of 0.1°C and relative humidity uncertainty of 2%.

The second algorithm of calculating dewpoint temperature is a polynomial formula. The dewpoint temperature depression is (Schlatter, 1990)

\[
T - T_d = (14.55 + 0.1147T)X + [(2.5 + 0.007T)X]^{1/3} + (15.9 + 0.117T)X^{14}
\]

where \( X = 1 - \text{RH}% \). The algorithm for calculating saturation vapor pressure based on the air temperature and relative humidity was given by Buck (1981).

The accuracy of the humicap RH element together with signal conditioning circuits can be ±2 to ±3% with ±1% stability per year, so annual calibration is recommended by manufacturers. The common calibration device is a dewpoint generator (e.g., LI-610 dewpoint generator) with ±0.2°C calibration error under proper operations.

**Cloud Ceiling Height**

Clouds are important to climate because they strongly modulate incoming solar and outgoing thermal radiation. Clouds, as the source of precipitation, are also a key element in the hydrologic cycle. Clouds are currently under intense scrutiny by researchers to gain a better understanding of their role in our environment. The instruments to measure the cloud bottom heights generally employ pulsed diode laser Lidar (Light Detection and Ranging) technology, where short, powerful laser pulses are sent out in a vertical or slant direction. The directly backscattered light caused by molecules, aerosols (dust), and cloud (water or ice) particles in the atmosphere is measured as the laser pulses traverse the sky. A ceilometer (for example, Vaisala Models CT12K or CT25K) essentially measures the backscattered light intensity from a pulsed InGaAs diode laser (905 nm) as a function of distance. The operating principle of the CT12K or CT25K ceilometer is based on measurement of the time needed for a short pulse of light to traverse the atmosphere from the transmitter of the ceilometer to a backscattering cloud base and back to the receiver of the ceilometer. Because the total distance traveled includes a path from the transmitter to the
cloud and back again, the actual height of the cloud (from the transmitter) is actually one-half of the total distance. The calculation can be expressed as:

\[ h = \frac{ct}{2} \]

where \( h \) is the height of the cloud, \( c \) is the speed of light (\( 9.8356 \times 10^8 \) ft s\(^{-1}\)), and \( t \) is the time from the transmission to the reception. For example, a cloud detected 24.4 microseconds (\( \mu s \)) after transmission indicates a cloud at 12,000 feet.

The ceilometer cloud sensor based on Lidar technology actually is one of the most complicated sensor systems developed for weather station networks. The detailed specifications for the transmitter and receiver optics, the return signal detecting algorithm, and the noise cancellation techniques cannot be presented here because of space limitations. A few important specifications are selected for discussion below. The measurement range is 12000 ft for the CT12K and 25000 ft for the CT25K. The sampling area of cloud (60-ft resolution for the CT12K) depends on the detector’s field of view divergence. The vertical resolution of measurement depends on the sampling rate of return signals and is 50 ft for both the CT12K and CT25K. The output of a ceilometer cloud sensor, which is microprocessor-based, is digital output formats via one or two RS232 ports (one is for the data message output and the other is for sensor configuration and maintenance interaction by users). The laser diode wavelength is at 905 nm. The system bandwidth (-3dB) is automatically selected based on signal gain. The measurement cycle is programmable. The system accuracy is expressed in terms of percent against hard target (e.g., ±2% ± 0.5 resolution against the hard target for the CT25K).

Two calibration procedures are used to verify and/or optimize performance of the Vaisala ceilometers. Factory calibrations include testing transmitted and received laser power, optical alignment, and pulse timing electronics. The results of these tests are available from the microprocessor in the sensor system, which can be accessed by users. The other calibration procedure is to calibrate the ceilometers by tipping the instrument to a near-horizontal position and aiming the beam at a known object more than 100 m distance. The “instrument health” data in the output files are used to diagnose a possible instrument malfunction. The “instrument health” data are of sufficient detail to pinpoint a failing or failed component or subsystem.

**Solar Radiation**

Solar radiation is usually expressed in terms of the energy flux density of shortwave radiation (0.3 to 3 \( \mu m \)) directly from the sun and indirectly from scattering processes in the sky. Two types of sensors, thermoelectric and photoelectric, are commonly used in solar radiation measurements at AWS sites. Thermoelectric sensors are commonly designed to respond equally to incident energy over the wavelength range. Typically, thermoelectric sensors (thermopile) consist of a temperature sensor such as one junction of thermocouple attached to a surface that is painted with a highly absorbent black paint. The reference temperature sensor is attached to either the instrument housing or a white reflective surface in the same radiation field as the black surface. The difference in temperature between the black surface and the reference is then a function of the difference in
absorbed radiation. It is important that the other energy exchanges (such as convection and conduction) from the two surfaces be similar. Typically the surfaces are covered with glass or polyethylene domes to minimize convective losses and keep them similar. The commercial pyranometers of thermoelectric sensors are the Eppley Model PSP (Eppley Laboratories) and the Kipp and Zonen Model CM11 (Kipp & Zonen). The sensitivity of this type of pyranometer is around 10\(\mu\)V W\(^{-1}\) m\(^2\), depending on the number of junctions of the thermopile.

Photoelectric sensors are solid-state detectors that are very useful because of their low cost and spectral response characteristics. This type of pyranometer usually contains a photoelectric element (e.g., silicon diode) and a diffuser head (cosine-corrected head), which is used to improve the Lambert’s law response (compared to a bare photoelectric element). The relative spectral response of a semiconductor such as the silicon photodiode pyranometer (e.g., LI-200S pyranometer) does not extend uniformly over full solar radiation range (e.g., 0.4 to 1.1 \(\mu\)m for LI-200S). Changes in the spectral distribution of the incident radiation, coupled with the non-uniform spectral response of the photodiode sensor, can cause errors in the sensor output. For this reason, the manufacturers do not recommend use under artificial lighting or within plant canopies. Reflected radiation is also erroneously measured. The continuous current signal output (\(\mu\)A level) of the photodiode pyranometer requires either a shunt resistor (e.g., 100 ohms) to provide a voltage signal with a sensitivity of several \(\mu\)V W\(^{-1}\) m\(^2\) or a current-to-voltage amplifier (low input bias current op-amp) to directly condition the signal from the photodiode. The latter has the advantage of giving a higher signal and a lower temperature coefficient for the output than operation with a shunt resistor method.

The types of error, often quoted for solar radiation sensors, are the cosine error, azimuthal error, spectral error, and temperature dependent error. The cosine error is defined as departures from the ideal cosine response (LI-COR, 1986 and 1991). The azimuthal error refers to changes in the output when the azimuthal angle is varied. The spectral error of thermoelectric sensors, a deviation from the ideal spectral response (Ross and Sulev, 2000), usually is smaller than that of the photoelectric sensors. The ambient temperature dependance refers to changes in output resulting from changes in temperature. Another possible error source is systematic errors related to leveling of the sensor (Linkosalo et al., 1996). Calibrations of the photoelectric sensor (e.g., LI-200S) can be taken by comparing it with thermoelectric sensors (both Eppley Model PSP and Kipp and Zonen Model CM11 are considered as the secondary standards) under three consecutive clear sky conditions. The pyranometers model PSP and model CM11 should be returned to the manufacturers for calibrations with the World Radiation Reference (WRR) or WRR traceable devices.

**Precipitation**

The liquid precipitation accumulation is usually measured by the tipping bucket rain gauges or weighing gauges at the AWS site. Obviously the principle of weighing gauges is based on the weight of accumulated precipitation on a spring-loaded or balanced lever platform. The position of loaded balance can be used to indicate the liquid precipitation accumulation by a linear variable differential transformer (LVDT) sensor or a simple potentiometer. The voltage signals proportional to precipitation are obtained from the LVDT or potentiometer. Because of the higher cost and relatively greater long-term main-
tenance of the weighing gauge, tipping bucket rain gauges are widely used (e.g., Texas Electronics Inc. model TR525I and Friez Engineering Co. model 7405HA). The tipping bucket is located under a funnel in the collector housing. The bucket is a two-chamber container that pivots on a centered fulcrum. Precipitation flows through the funnel into one compartment until enough precipitation (e.g., 0.01 inch rain [0.245 mm]) is present to tip one side of the bucket down. Thereupon it empties and the other side begins to fill. The amount of weight that causes the bucket to tip is the resolution of the gauge. The tipping motion activates a mercury switch (or reed switch), thereby establishing a momentary closure for each unit resolution of rain. The output from the tipping bucket is one electrical pulse for each unit of precipitation collected.

One important source of errors in precipitation measurements is the error caused by precipitation intensity. A high intensity of precipitation causes incomplete dumping of the tipping bucket rain gauges. Increasing the volume of the bucket can improve rain intensity dependence but decrease the resolution of the rain gauge. The other sources of errors are wetting loss and wind-induced errors (Metcalfe et al., 1997). Snowfall or other solid precipitation cannot be accurately accumulated into liquid precipitation by a non-heated tipping rain gauge. The temperature sensing for detecting possible solid precipitation occurrence (e.g., temperature less than 40°F) is simple and practical at the AWS site, but the heating power is not always available at remote sites. The rain gauges (both tipping bucket and weighing rain gauges) can be simply calibrated by slowly pouring 10 times the water required for one unit resolution (one tip) into the rain gauge with a flow rate of 10 tips per minute. The signal output must be 10 ±1 pulses or 10 ±1 tips to maintain sufficient accuracy (1% at 2 inches/hour or better).

**Wind Speed and Direction Sensors**

Wind speed sensors used for atmospheric measurements fall into two broad categories: mean wind speed sensors and instantaneous wind speed sensors. Rotation anemometers such as cup anemometers, propeller anemometers, and rotation vanes are apparently the most common sensors for the mean wind speed measurements at the AWS. The hot-wire anemometers and sonic anemometers are instantaneous sensors traditionally used in atmospheric turbulence work. Certainly the mean wind speed sensors cannot be used for instantaneous wind speed measurements, but they are suitable for wind speed measurements (Met One Instruments, Inc. model 014A) at the AWS because they are rugged, dependable, and relatively inexpensive. Both cup anemometers and vanes depend on moving parts coming into dynamic equilibrium with the flow.

Cup and vane systems are marketed in a variety of shapes and forms. The most common configuration is a three-cup anemometer and direction vane mounted side by side at the ends of a T-shaped horizontal boom. Both rotate on vertical axes, so they are separated horizontally to avoid mutual interference. The advantage of the cup anemometer is that it can accept winds from any direction (only the directions blocked by the wind vanes and the supporting mast would be considered unfavorable). Currently the most popular designs for the mean wind speed measurements by cup anemometers are (1) using a reed relay contact by a rotating magnetic field (e.g., Met One Instrument Inc. model 014A), (2) generating alternating current (AC) sine wave voltage signal with frequency directly proportional to wind speed (NovaLynx Co. model 200-03002), and (3) using a photochopper
device to provide a frequency output (NovaLynx Co. model 200-F460). The mean wind speed measured from the cup anemometer is a linear function of rotation frequency of the cup. For wind vanes with potentiometer systems that read vane position, the gap in the resistance element, typically a 10° sector, is often pointed in the direction of the mast to keep the number of unfavorable directions to a minimum.

Several important specifications in wind speed sensors are angular response (cosine response or direction sensitivity), frequency response (combining the time constant and distant constant), and starting speed (threshold). Cup anemometers can be periodically calibrated in laminar flow in a wind tunnel to obtain an accuracy of ±1 to ±2%. The distance constant (63% response time constant converted to distance) is between 1.5 and 5 m, and starting speeds are typically 0.5 m s⁻¹. There is a tendency in cup anemometers to overspeed, resulting partly from their nonlinear response to wind speeds, which is due to their angular response characteristics. Reports of overspeeding error generally range from 5% to 10%, depending on the intensity of turbulence (sometimes it can reach 30%) (Izumi and Barad, 1970; Busch and Kristensen, 1976; Kaganov and Yaglom, 1976; and Wyngaard, 1986).

Summary

There are a variety of options for choosing meteorological sensors used at AWS because of the emergence of new sensors and the requirements of new applications. Some sensors related to agricultural and environmental applications, such as ultraviolet (UV) radiation sensors, photosynthetically active radiation (PAR) sensors, soil temperature and soil moisture sensors, and atmospheric trace gas sensors (CO₂ and other gas sensors), will possibly be introduced into the AWS networks in the future. All sensors have inherent advantages and disadvantages, depending on specific applications. However, consideration of the required accuracy and stability of sensors, ease of maintenance, and comparative cost may help network operators make informed decisions in choosing sensors. The measurement errors of a sensor generally propagate in an additive fashion. Consequently, the total error for a measurement system equals the square root of the sum of root mean square error for each independent error component. Therefore, the sensor accuracy cannot represent the measurement errors that are inherent in the environmental changes, degree of coupling to the atmosphere, installation problems, periodic calibration and maintenance, and data acquisition system (data logger). Preventive and periodic sensor testing is always the best way to keep high-quality data at the AWS networks.

References


Single Station Quality Control Procedures

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Abstract

Automated weather stations (AWS) have become increasingly more common over the past 20 years. This chapter discusses the development and implementation of screening rules for the data collected by AWS, presents some statistical bases for such screening rules, and explores other possible screening methods. Three rules developed for screening stream gauge records—the high/low range limit rules (LIM), rate-of-change limit rule (ROC), and continuous no-observed-change with time limit rule (NOC)—were adapted for screening an AWS data record; experiences with these procedures are discussed. The authors note that the use of screening procedures can result in more reliable data records if used as part of an overall quality control/quality assurance (QA/QC) program. Such a program starts with proper siting and setup and is followed by set regular maintenance and set routine operational checks and practices. They also note the importance of determining user needs, given the multipurpose nature of most AWS, and recommend the development of a policy or protocol for turning data over to users.

Introduction

For about the last 20 years of the 20th century, individual and networks of automated meteorological stations have been installed throughout the United States and many other countries. For a variety of reasons, generally multiple purpose usage including real-time applications, the data collected are being archived in databases. The data record may include hourly or other subdaily periods and daily total or average values for solar radiation ($R_s$), net radiation ($R_n$), soil heat flux ($G$), precipitation ($P$), barometric pressure ($P_b$), water vapor pressure ($e$), wind speed ($u$), wind direction ($\theta$), air temperature ($T_a$), infrared surface temperature ($T_s$), and soil temperatures ($T_s$). Although screening the data record is the subject at hand here, overall quality control and quality assurance (QC/QA) involves a great deal more. Proper siting and setup followed by routine site and station maintenance, clock checks with a set clock standard, micrologger operation and data transfer checks, independent instrument checks, dual sensors, and periodic sensor recalibration or replacement are all recommended practices (see, e.g., Howell et al., 1984).

Meek and Hatfield (1994) discussed QC/QA for AWS data and outlined various possible methodologies. Although the importance of screening hydrological data has been independently argued (see, e.g., Mosley and McKercher, 1993), Meek and Hatfield (1994) adapted O'Brien and Keefer's (1985) three rules for screening stream gauge records—LIM, ROC, and NOC. Theoretically based, dynamic and/or static climate based, or instrument range based versions of these rules were developed and evaluated for screening an AWS data record. The rules were offered as a heuristic and not explicitly statistical approach to data screening and not as absolute or rigid rules. Users should adapt them according to given instruments, available information, and particular goals and constraints. This work presents some statistical bases for such screening rules and points to some other possible methods. In addition, Meek and Hatfield's (1994) original results are re-
viewed and further developments along with operational experience with and recommendations for using the methodology are provided.

**Basis for the Development and Implementation of Screening Rules**

Some possible bases for developing LIM, ROC, and NOC rules could be theoretical considerations based on the science of the sensor and/or parameter, static or dynamic empirical trends based on the World Meteorological Organization (WMO) 30-year climate record (WMO, 1967), or static empirical bounds based on sensor specifications. These rules have a statistical basis in the standard Shewhart chart (Figure 1a) from classical QC/QA procedures (see, e.g., Ch. 17, Box et al., 1978). Shewhart charts and other standard statistical procedures can help with checking the AWS data record and can be usefully employed in climate analysis (see, e.g., Hirsch et al., 1993). Another QC/QA chart, the cusum (for *cumulative sum of deviations*) chart (Figure 1b), can help with assessing bias and drift with regard to independent measurements like routine hand-held instrument checks or comparison between dual sensors at the site or between like sensors at adjacent stations. Both charts use the idea of data splitting/cross-validation because the acceptable norm and bounds are developed from an independent data set.

The AWS data record is actually a time series for each variable, so screening or analysis can be improved with the use of appropriate time-series methods (e.g., Salas, 1993). Many AWS variables are serially correlated; hence, screening methods must consider this matter (e.g., Meek et al., 1998 and 1999). For example, the confidence interval in the Shewhart chart (Figure 1a) could be wider or the bias shown in the cusum chart (Figure 1b) could be insignificant after the correct degrees of freedom are estimated from the given correlation structure. Moreover, just as spatial statistics can readily be employed to estimate a value with a confidence interval for a missing or unobserved location, time-series methods can be so employed for a single station variable’s record.

Methods from statistical graphics (e.g., Cleveland, 1993 and 1994; or Tufte, 1983, 1990, and 1997) and exploratory data analysis (EDA; see Hoagland et al., 1983) like coplots or panels on related sensors, variables, or all three of the screening rules for the same variable can be most revealing. A paneling scheme has been used for most figures in this paper. Panel graphs of variables on the same sensor like $u$ and wind direction or $T_s$ and $e$ or dew point, or the LIM and ROC rules for a given variable, are helpful. For a given variable, QC/QA charts can make use of unique frequency and distributional properties for the annual, seasonal, daily, or subdaily record (e.g., Stedinger et al., 1993). For example, a printer graph composite of standard EDA graphs (Figure 2) reveals interesting distributional properties of hourly wind speed.

Sensitivity/error analysis can assess data problems with specific estimates calculated from AWS data like evapotranspiration (see, e.g., Ch. 17, Box et al., 1978); Beven (1979) provides a Penman-Monteith evapotranspiration example. Theoretical, empirical, or sensor-based information can be used to derive valid domains for calculated variables. For example, Ohmura (1982) defines valid and invalid domains for the Bowen Ratio ($\beta$) in the $\Delta T$ and $\Delta e$ plane based on a reasonable range for $\beta$ and reasonable precision limits for $\Delta T$ and $\Delta e$. 

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Figure 1. (a) The Shewhart chart showing an independent observation sequence plotted within previously defined confidence bounds and guided by an expected or normal value. (b) The corresponding cumulative sum of differences (cusum) chart shows an early-on positive bias followed by a drift after observation 10. The example is adapted from Box et al. (1978:561).
Figure 2. On the left of this montage of exploratory data analysis plots is a stem-leaf plot of the 30-year record for hourly wind speed data from Des Moines, Iowa (WBAN 14933). It is a table form of a histogram and shows a bimodal distribution with a large number of zero values (≈3%) and a non-normal right-skewed distribution of positive non-zero values with a large number of outliers in the tail. The middle graph is a box-whisker plot that depicts quantile-based scales for the distribution. The box in the center represents the scale of the middle 50% of the data or interquartile range, the third minus the first quartile (IQR = Q₃ - Q₁). The line in the middle of the box is the median (50th percentile). The + sign is the arithmetic mean. The bottom whisker stops at the minimum value because it is less than Q₁ - 1.5IQR. The top whisker stops at Q₃ + 1.5IQR. Data above that are considered outliers with the * representing values > Q₃ + 3IQR. The figure on the right is a Quantile-Quantile (QQ) plot. Were the data normal, the QQ plot would be a straight 45° line without tails.
Figure 3. The dynamic Shewhart chart for air temperature uses cosine trends for the norm and extremes developed from the 30-year record for the Iowa State Experiment Station. The data are all 1994 daily averages from a close-by AWS used for one of our labs’ research projects.

There are several options for modeling the normal and bounding curves for the dynamic climatic LIM- and ROC-based rules. One approach is to use loess, splines, or nonparametric curves (e.g., Cleveland, 1993). Another is to use generalized least squares regression (e.g., Carroll and Ruppert, 1988). Starting with the Fourier base functions, cosines series or Marr wavelets are recommended parametric curve forms for fitting the respective trends. Figure 3 shows an example of a Shewhart chart for air temperature using cosine trends for the climatic norm and extremes.

These rules can be implemented in different ways. Although the rules have graphical interpretation, they can be automated by the computer data processing program so each questionable datum is automatically flagged without human intervention or judgment. The job could be done in real time at the AWS site with some of the high-end programmable microloggers now available. The rules can, however, be done with interactive graphics or by post processing graphics and data summaries. Also, as we do at the National Soil Tilth Laboratory (NSTL), a combination of both methods can be used. Eventually a conditional rule base or expert systems that goes well beyond ideas in Reek et al. (1992) could be employed to identify common problems that emerge from this dual inspection process with the potential to detect anomalies caused by frontal passages, stuck or drifting sensors, and so much more!
Experience and Further Developments with Screening Procedures

Meek and Hatfield's (1994) dynamic climatic-based rules were developed only for $R_s$, $T_s$, and $T_a$ because development data were readily available through National Weather Service Coop Station publications and Iowa State University records and data files. The hourly $R_s$ rule was screened theoretically by using an estimated extraterrestrial value ($R_{set}$). The daily $P$ maximum was a fixed constant estimated by adding 10 mm to the largest value from the 30-year record. The daily $P$ minimum was set at a world record low observed value. The remaining rules were instrument range based. Hourly and daily data from well-maintained automated weather stations in Walnut Creek Watershed at Kelley, Iowa (9 months), and Treynor, Iowa (1 year), were used to evaluate and refine the screening rules. Results were as follows: Daily data were not flagged often. The most common flag, on either time scale, was on water vapor pressure when its value exceeded the 95% relative humidity calibration limit of the sensor (actually we used <0.96). Hourly $R_s$ often exceeded a computed $R_{set}$ value, but mainly at sunset hours when the cosine error of the sensor is high. The LIM rule is mainly invoked via observations outside the climatic limits or the sensor ranges; the ROC rule flags abrupt changes; the NOC rule flags unusually steady periods in the data stream.

Since publication of this analysis, there have been continuing improvements and interesting results at other locations. Initially the upper bound for daily $R_s$ LIM rule ($R_{se}$, also known as a clear day curve) was developed from an interpolating curve for selected clear-day data from the Ames daily $R_s$ record from 1960 to 1990. Several selected values were removed because they exceeded daily $R_{set}$ and were thought to be blunders. Since then a theoretical daily $R_s$ bound was developed and examined for Ames and four other locations (Meek, 1997). It uses climatic low turbidity variable data developed from nearby sites in the Solar and Meteorological Observation Network (SAMSON) Database (NREL, 1992) input into an hourly incremented, daily totaled single-atmospheric-layer broadband radiative transfer model. The data for every site in the SAMSON database has been put through a QC/QA process. No datum from any three SAMSON sites used in the study exceeded the developed $R_{se}$ boundary. The Ames data were then reexamined and 50% of the Ames $R_s$ data were found to exceed $R_{se}$. Almost all of the questionable observations were from the first half of the record, when daily integrations were obtained via the use of a planimeter and seemed to have about 5% high bias. A similar result was found for the $R_s$ data from Wooster, Ohio.

Similar screening rules for checking AWS data were developed for a station in Piketon, Ohio. Hourly $R_s$ data often exceeded $R_{set}$ by more than 0.5 MJ m$^{-2}$ for a few hours before sunset on a regular basis. Dr. John Prueger of the NSTL went to the site and found that there was a large embankment east of the station that was enhancing reflection during the sunset period. Hence the location of the station was poorly chosen.

The SAMSON site nearest to Ames is the Des Moines Airport record (WBAN 14933); it is about 53 km due south. Having obtained the WBAN 14933 record, the consideration of dynamic screening rules for some of the other AWS variables became possible and most revealing (Figures 4 and 5). Plots of the median (50 percentile) and extremes of daily $P_v$,
(a) Daily Average Air Pressure, kPa

(b) Daily Average Air Pressure Change, kPa

Day of the Year

Figure 4. (a) Daily data for the air pressure norm and extremes from the 30-year record for Des Moines, Iowa (WBAN 14933). The gray dashed line is the 106 kPa instrument limit based static rule upper bound listed in Meek and Hatfield (1994); the lower bound of 88 kPa is off scale. (b) Corresponding norm and extremes for daily data air pressure change; Meek and Hatfield (1994) bounded the absolute daily change by 4 kPa.

$\nabla P$ (here, $\nabla$ is the symbol for a backward [in time] difference operator), $u$, and $\nabla u$ versus day of the year show that the static LIM and ROC rules should be dynamic and much more restrictive than the sensor range based rules used in Meek and Hatfield (1994). For the NOC rules, frequency analyses reveal that daily $\nabla P = 0$ and $\nabla u = 0$ are extremely rare events, representing 0.38% and 0.13% of the data (42 and 14 occurrences in the 30-year
Figure 5. (a) Daily data wind speed norm and extremes from the 30-year record for Des Moines, Iowa (WBAN 14933). The gray dashed line is a 10 m s\(^{-1}\) static rule upper bound that is arbitrary. Nonetheless it is still much less than the 45 m s\(^{-1}\) instrument based static limit rule in Meek and Hatfield (1994); the lower bound is 0. (b) Corresponding norms and extremes for daily data wind speed change; Meek and Hatfield (1994) bounded the absolute daily wind speed change by 10 m s\(^{-1}\).

period of daily record, respectively). Analysis of the 30-year \(P\) record for Ames reveals that for \(\approx 95\%\) of observations, \(P = 0\). Furthermore, the maximum \(P\) values nearly follow the phase and sinusoidal annual trend of maximum daily \(T_s\).
Summary and Recommendations

In general, the results and recommendations of Meek and Hatfield (1994) still stand, based on assessing almost 10-year records at multiple sites. Data processing rules are only one component of assuring and assessing AWS data quality. Routine use of screening rules will result in a more reliable record as well as help with data exploration and further analysis and modeling of the climate record.

It is important to assess who needs the data and for what purpose because most AWS stations collect data for multiple purposes. What may be sufficient for one purpose may not be for another. For example, the actual vapor pressure or dew point value from certain humidity sensors may be uncertain near the saturation point, but for practical purposes the air can be considered saturated. So the users must assess their own needs. Hence a policy and/or protocol for turning over data to users is highly recommended: the Oklahoma Mesonet provides a good example. We suggest following the recommendations of the Sensors and QC Discussion Section at the conference (see the report of Working Group C). In summary, they are:

1. Strictly adhere to siting and setup guidelines.
2. Record the maintenance history and values of the regular independent sensor checks.
3. Theoretical and/or climatic-based rules are better than instrument limit/range rules.
4. Climatic-based rules are best developed from high-quality databases like SAMSON.
5. Combine automated data processing rules with exploratory and panel graphics.
6. Have a data transfer policy with a written statement explaining the entire QC/QA process. Include the document whenever data are made available to users.
7. Network QC/QA procedures could make use of these findings. In addition, they could be imposed on top of single-site procedures.

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Acknowledgments

The work was supported by the USDA–ARS–MWA NSTL, Ames, Iowa, Dr. J.L. Hatfield, Director. Professor R.E. Carlson, Iowa State University (ISU), Ames, commented on the manuscript and provided the Ames data file. The staff of the ISU Agronomy Farm, Boone, Iowa, collected and recorded the Ames historical data. Mr. L.A. Kramer and the staff of the USDA–ARS–MWA–DLRS, Trenor, Iowa, collected and recorded the Trenor data. Mr. K. Cole, USDA–ARS–MWA NSTL, has maintained the AWS stations, utilized the in-house rules for years, and provided comments and feedback on the whole process. Drs. John Prueger and Tom Sauer, USDA–ARS–MWA NSTL, provided general support and advice for the whole process. Finally, thanks for the ideas and feedback from all members from the Sensors and QC Discussion Section at the conference for which this chapter was prepared.

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Multiple Station Quality Control Procedures

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Abstract

Quality control of data is necessary to maintain credibility of data sets. Multiple station networks face additional quality control challenges in comparison to single stations. This chapter discusses quality control procedures used by the Automated Weather Data Network, which comprises 148 stations located primarily in the Great Plains.

The quality control program of the AWDN is a set of generalized procedures that test whether the data falls into reasonable intervals. Using additional statistical techniques allows AWDN staff to screen bad data and make data estimates when data is not reported. Estimates based on regression weighting generally have less systematic bias than estimates based on inverse weighting techniques, but this advantage is lost if data gaps are too large to allow calibration of the weighting. The chapter concludes that better quality control procedures are needed.

Introduction

When quality control is to be conducted, several additional possibilities come into play with a multiple station network in contrast to working with quality assurance on a single station basis. This paper deals with the quality control procedures used in the Automated Weather Data Network (AWDN) operated as a state cooperative primarily by the states of Iowa, Kansas, Nebraska, North Dakota, and South Dakota. Some stations from Colorado, Minnesota, Missouri, and Montana are also included in the network. As of March 2000, the number of stations taking data in the AWDN was 148.

Each datum stored in the AWDN archive, whether hourly or daily, carries a quality flag. The flag is blank for "good" data. The flag is "E" for data estimated by inverse distance weighting or by other estimation procedures. The flag "R" is for estimates based on a regression weighting method. As a last resort, the data is sometimes estimated based on data from the hour (or day) before. This data carries the "e" flag. The flag "M" is also used in the data base, but it is usually a temporary flag that indicates the data were not reported. Estimates usually replace the missing flag during the quality control procedures.

Likewise, every variable has a unique code. For example, hourly average temperature has the code 100.

Procedures

The quality control program was written in FORTRAN. It was originally conceived as a set of generalized procedures. The concept was to have the variable codes, associated procedures, and any auxiliary information (thresholds, etc.) in the input stream. This design was chosen because it makes it possible to avoid the problems associated with
generating variable specific code. This method also allows one to add a new variable to
the quality control process without writing new sections of code or recompiling the pro-
gram.

The generalized procedures are defined below:

<table>
<thead>
<tr>
<th>Procedure #</th>
<th>Subroutine name</th>
<th>Action</th>
<th>Flag on failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SETNEG</td>
<td>Sets negative values to zero</td>
<td>blank</td>
</tr>
<tr>
<td>2</td>
<td>SUNTIM</td>
<td>Checks solar values against sunrise and sunset</td>
<td>M</td>
</tr>
<tr>
<td>3</td>
<td>HILO</td>
<td>Compare to limits; alert, no change to original data</td>
<td>blank</td>
</tr>
<tr>
<td>4</td>
<td>HILO</td>
<td>Compare to limits; set to threshold</td>
<td>E</td>
</tr>
<tr>
<td>5</td>
<td>HILO</td>
<td>Compare to limits; set to zero</td>
<td>M</td>
</tr>
<tr>
<td>6</td>
<td>FLAGME</td>
<td>If precip is 0 and flag is M</td>
<td>E</td>
</tr>
<tr>
<td>7</td>
<td>MAXMIN</td>
<td>If variable 1 &gt; variable 2, set both flags</td>
<td>M</td>
</tr>
<tr>
<td>8</td>
<td>MAXMIN</td>
<td>If variable 2 &lt; variable 1, set both flags</td>
<td>M</td>
</tr>
<tr>
<td>9</td>
<td>NOCHNG</td>
<td>Counts the number of intervals that variable is constant, alerts</td>
<td>blank</td>
</tr>
<tr>
<td></td>
<td></td>
<td>operator of the longest sequence (&gt;0)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>HILO</td>
<td>Compares to threshold, set to threshold</td>
<td>blank</td>
</tr>
<tr>
<td>11</td>
<td>UPSET</td>
<td>If var &gt; upper threshold, set to upper threshold</td>
<td>blank</td>
</tr>
<tr>
<td>12</td>
<td>DNEST</td>
<td>If var &lt; lower threshold, set to lower threshold</td>
<td>M</td>
</tr>
<tr>
<td>13</td>
<td>ACCUM</td>
<td>Accumulates variable 1 into variable 2</td>
<td>blank</td>
</tr>
<tr>
<td>14</td>
<td>GDD</td>
<td>Accumulates GDD from max &amp; min temp</td>
<td>blank</td>
</tr>
<tr>
<td>15</td>
<td>ETCHK</td>
<td>Calculates the potential evapotranspiration (Penman)</td>
<td>blank</td>
</tr>
<tr>
<td>17</td>
<td>CHGNUM</td>
<td>If flag is C, then var = A + B * var</td>
<td>blank</td>
</tr>
<tr>
<td>18</td>
<td>SCHK</td>
<td>Check if solar &gt; clear sky value</td>
<td>E</td>
</tr>
<tr>
<td>19</td>
<td>MAXMIN1</td>
<td>If variable 1 &lt; variable 2, then increase counter</td>
<td>blank</td>
</tr>
<tr>
<td>20</td>
<td>MAXMIN1</td>
<td>If variable 1 &gt; variable 2, then increase counter</td>
<td>blank</td>
</tr>
</tbody>
</table>

The design allows the program to run any number of the procedures on a given variable. The user specifies the procedures that will be used for each variable by tagging the variable codes with procedure numbers in the input stream.

**Missing Data and Estimates**

The term *missing data* is not accurate because data are not collected and then lost, but it is used to denote situations when no data are available for a given variable. This could be because of a sensor failure or a failure to make the communications link with the station. Such variables in the system carry the flag “M.”

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If the variable is totally missing during the QC period, then an inverse distance weighting technique is used to estimate the data and a flag of “E” is assigned. A separate program is used to sort through the stations for each variable and for each year of record to note the closest stations on which the estimate will be based. The formula for this estimate is:

\[ v_i = \sum \{(D_{ij})^p V_j\}/(D_{ij})^p \]

where lower case indicates an estimate and upper case V indicates actual data. The subscript i indicates the missing station, j indicates the surrounding stations, and p is the exponent, taken as a -1. \( D_{ij} \) is the distance between the i'th and j'th stations. The summation proceeds over the five closest stations or as many of the five that have data. The estimate is not made unless at least two surrounding stations are available.

**Screening Data Using Surrounding Stations**

We screen data at a station using the data from surrounding stations. The first step is to calculate the following statistical indicators:

- \((r_{ijk})^2\) = the explained variation between station i and its neighbor (j), at time lag \((k = -1)\), concurrent time \((k = 0)\), and lead time \((k = 1)\)
- RMSE_{ijk} = the root mean square error for the regression of i on j for time k
- \( A_{ijk}, B_{ijk} \) = the constants in the best fit equation \( v_{ijk} = A_{ijk} + B_{ijk} V_j \)

The time offset \( k (-1, 0, 1) \) on the sampling interval was introduced for stations where hourly data may be collected on opposite sides of a time zone boundary (it is also useful for COOP data when the time of observation is different from station to station). The above statistics are calculated and used, unless the number of samples available is less than 10, or the explained variance \((r^2)\) is less than 30%.

Five intermediate estimates are possible for each time lag, one for each surrounding station. The best time offset is chosen on the basis of the RMSE_{ijk} values. The five best estimates based on each surrounding station are then formed:

\[ v_{ijk} = A_{ijk} + B_{ijk} V_j \]

Here \( k' \) indicates the “best” lag \((-1, 0, \text{or} 1)\), defined according to the smallest RMSE between station i and station j.

A data value is considered bad if it fails to fall within specified confidence intervals for all five station pairings:

\[ v_{ijk} - F \text{ RMSE}_{ijk} < V_i < v_{ijk} + F \text{ RMSE}_{ijk} \]

where F defines the desired confidence limits. Assuming that the estimates are normally distributed about the best fit line, an F value of 2 indicates that 94.45% of the values should lie within these confidence intervals; an F value of 3 indicates that 99.73% of the values should lie within the confidence intervals. F is a specified input to the program that is variable specific.
Finally, the five best estimates are combined into a single estimate by weighting according to the RMSE.

\[ v_i = \sum \frac{(RMSE_{ik})^2 v_{ik}}{(RMSE_{ik})^2} \]

This estimate is used when the data value fails the above tests, in which case \( V_i \) is replaced by \( v_i \) and the flag is set to R to indicate a regression-based estimate. The \( v_i \) value is also used when the original flag for the data was M if sufficient samples were available during the QC period to perform the required statistical analysis. Precipitation is not addressed by the regression-based approach, owing to the high spatial variability.

**Seasonal Thresholds**

For variables that undergo seasonal variation, it is better to define thresholds that vary with time of year. The maximum and minimum daily temperature are good examples of this type of variable. A simple approach to this is to define an annual upper and lower limit on temperature during the year.

If \( T_{u183} \) is the upper limit on temperature during the hot season, and \( T_{w0} \) is the upper limit on temperature during the cold season, then the upper limit on temperature on any day (d) can be specified as:

\[ T_{ud} = T_{w0} + (T_{u183} - T_{w0}) \cos \left\{ 0.5 \pi (d - 183)/183 \right\} \]

Similarly, for the lower limit on temperature for any day we have:

\[ T_{ld} = T_{w0} + (T_{l183} - T_{w0}) \cos \left\{ 0.5 \pi (d - 183)/183 \right\} \]

These values represent a finer screening than is possible by assuming a single upper and a single lower limit, independent of time of year.

**Summary**

Quality control of incoming data streams is essential to the credibility of the data set. Often it is the notification from the quality control software that first alerts the staff that there is a problem with station sensors or other equipment.

A number of procedures can be defined to test whether data falls into reasonable intervals. In addition, statistical techniques have proved useful for screening bad data and making data estimates when data is not reported. In general, estimates based on regression weighting have less systematic bias than estimates based on inverse distance weighting techniques. However, this advantage is lost if data gaps become so large that the calibration (RMSE) of the weighting cannot be performed.

Better QC procedures are needed, particularly for precipitation.

**Further Reading**

For more information, see Chapter 12, “Single Station Quality Control Procedures.”
Data Management, Data Access, and Application
Système Intégré de Suivi et Prévision, an Integrated Information System for Monitoring Cropping Season by Meteorological and Satellite Data: An Application in Niger

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Institute of Agrometeorology, Florence, Italy

Abstract
The SISP (Integrated Information System) has been developed by CeSIA (Center for Informatics Application in Agriculture) and IATA (Institute of Agrometeorology and Environmental Analysis for Agriculture) of Florence in collaboration with the Meteorological Service of Niger, the CILSS (Comité International pour la Lutte contre la Secheresse au Sahel), and Italian Cooperation Department.

SISP was developed after several years of experience in Niger and the Sahelian region with field experiments on millet eco-physiology, traditional agricultural production systems, and the effect of water stress. WMO (1993) summarizes the experiences in this field, and a number of scientific publications deal with different problems regarding millet production systems in Niger and application of simulation models and satellite image processing for crop monitoring and yield forecasting.

In collaboration with the AGRHYMET Center of Niamey, some international workshops have been organized, and training for Nigerin personnel has been accomplished during the project activities.

The SISP was actually developed for Nigerin conditions, but it should be suitable for application in other Meteorological Services of CILSS countries, where the AGRHYMET Program has already improved the meteorological network and database. Because of the modular structure of SISP, the system can be exported to other countries and agricultural conditions, with a limited number of adjustments.

The upgraded version for Windows 95–98 is now available, after some years of experience in Niger. A new user-friendly interface makes integrations of both tabular data and cartographic information, including satellite images, a simple task.

This chapter provides a brief discussion of the SISP. For additional information, please consult the references ("Further Reading") at the end of the chapter.

General Overview of SISP
The main aim of SISP is to integrate different information sources and analysis procedures to allow the meteorological services a decadal perspective on growing season monitoring and to provide national early warning systems with useful information about the evolution of crop conditions.
The system was conceived following some basic criteria:

- the package must be sufficiently user-friendly to be easily applied by agrometeorologists and technicians of national meteorological services in CILSS countries, taking into account the actual facilities, software, and hardware available;
- inputs should be limited to information provided in real time from meteorological network and field observation sites;
- spatial units should correspond initially to administrative ones, in order to facilitate interpretation of results by decision makers at different levels;
- final results and products should facilitate and complete production of decadal agrometeorological bulletins;
- integration with software already used is recommended to avoid duplications of functions and capabilities already provided by other packages.

The system was organized into modules corresponding to tools the user can exploit. Principal tools of SISP are:

- statistical analysis procedures on historical series of rainfall data, to produce agroclimatic characterizations and to allow comparison between actual and reference values.
- a millet simulation model to be run at station level to estimate millet crop conditions and the effect of rainfall distribution on crop growth and yield.
- NOAA NDVI image analysis procedures to extract NDVI temporal profiles on relevant sites, in order to monitor vegetation conditions on pasture lands and main crop production areas of the country.
- analysis of MeteoSat images of estimated rainfall for early estimation of sowing dates and risk areas.
- production of tables, graphs, and maps for decadal reports usually produced by national meteorological services and national early warning units.

Rainfall analyses are of great importance in the Sahel, where rainfall can be considered the main limiting factor of crop production and the annual rainfall amount can explain about 70% of yield variability in this region. Notwithstanding this, a high variability exists in spatial rainfall distribution, cultural systems, and crops and vegetation conditions. This justifies the necessity of developing procedures for satellite image analysis in order to evaluate this variability, which cannot be appreciated by simple spatial interpolation techniques of meteorological data or agrometeorological parameters.

**Statistical Analyses**

Using the statistical approach, several agrometeorological parameters can be evaluated, first at station level: annual and decadal average rainfall, probabilities of rainfall amounts for each decade, date of the onset of the growing season (definition of reference dates for early, normal, and late onset), drought risk during the rain season. In a territorial approach and on the basis of historical series of data, as a first task, the main risk areas for agricultural production can be identified by an agrometeorological characterization of the
region. As a result of this analysis, a database of average and probable values of onset of the growing season, season length, and decadal precipitation is obtained. These values will be used for ten-day-period-based evaluations of the actual season.

Figure 1 shows the early evaluation of the onset of the growing season in 1993; it was published in the July 2 decadal agrometeorological bulletin by the National Meteorological Service of Niger. It includes the estimated length of season, calculated on the basis of correlation obtained with the statistical analysis. Similar comparisons of total rainfall amount for each station in the first decade of July of 1993 showed the late onset of the season, the scarce amount of precipitation in several areas of Niger, and some critical areas with rainfall amounts less than those of 1984 (at the same date), which was a very dry year.

<table>
<thead>
<tr>
<th>Stations</th>
<th>Moyennes 1961-1990</th>
<th>Estimation pour 1993</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Date de saison</td>
<td>Longueur de saison</td>
</tr>
<tr>
<td></td>
<td>Moyenne</td>
<td>Moyenne</td>
</tr>
<tr>
<td></td>
<td>(Jour)</td>
<td>(Jour)</td>
</tr>
<tr>
<td>AYOROU PTT</td>
<td>26-Jun</td>
<td>74</td>
</tr>
<tr>
<td>BANKILAIRE</td>
<td>29-Jun</td>
<td>64</td>
</tr>
<tr>
<td>BIRNI N’DOURO</td>
<td>31-May</td>
<td>114</td>
</tr>
<tr>
<td>BIRNI N’DOURNI</td>
<td>07-Jun</td>
<td>104</td>
</tr>
<tr>
<td>DAROU</td>
<td>06-Jul</td>
<td>64</td>
</tr>
<tr>
<td>DABOU LISIAERIG</td>
<td>21-Jun</td>
<td>64</td>
</tr>
<tr>
<td>DABOUL</td>
<td>29-Jun</td>
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</tr>
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<td>DIFFA</td>
<td>08-Jul</td>
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<td>114</td>
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<td>DOGOONDOUTCHI</td>
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<td>98</td>
</tr>
<tr>
<td>DOSSOU</td>
<td>29-May</td>
<td>114</td>
</tr>
<tr>
<td>FILINGUE</td>
<td>20-Jun</td>
<td>89</td>
</tr>
<tr>
<td>GAYA</td>
<td>19-May</td>
<td>129</td>
</tr>
<tr>
<td>GAZADOUA</td>
<td>10-Jun</td>
<td>101</td>
</tr>
<tr>
<td>GOURI</td>
<td>04-Jul</td>
<td>65</td>
</tr>
<tr>
<td>GUIDAM ROUMJII</td>
<td>21-Jun</td>
<td>87</td>
</tr>
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<td>ILELE</td>
<td>10-Jun</td>
<td>96</td>
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<td>KEITA</td>
<td>25-Jun</td>
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<td>LOGA</td>
<td>06-Jun</td>
<td>10</td>
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<tr>
<td>MADAJA</td>
<td>25-Jun</td>
<td>78</td>
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<td>MADAROUNDFA</td>
<td>07-Jun</td>
<td>106</td>
</tr>
<tr>
<td>MAGARIA</td>
<td>16-Jun</td>
<td>94</td>
</tr>
<tr>
<td>MAINE SOROA</td>
<td>30-Jun</td>
<td>73</td>
</tr>
<tr>
<td>MARADI AERO</td>
<td>13-Jun</td>
<td>96</td>
</tr>
<tr>
<td>MATAMAYE</td>
<td>16-Jun</td>
<td>98</td>
</tr>
<tr>
<td>MAYANGI</td>
<td>23-Jun</td>
<td>78</td>
</tr>
<tr>
<td>MYRIHIAI</td>
<td>18-Jun</td>
<td>87</td>
</tr>
<tr>
<td>NIAMEY AERO</td>
<td>02-Jun</td>
<td>112</td>
</tr>
<tr>
<td>OUALLAM</td>
<td>17-Jun</td>
<td>90</td>
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<td>SAD</td>
<td>04-Jun</td>
<td>107</td>
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<td>TAHOUA</td>
<td>17-Jun</td>
<td>93</td>
</tr>
<tr>
<td>TANONT</td>
<td>09-Jul</td>
<td>54</td>
</tr>
<tr>
<td>TERA</td>
<td>15-Jun</td>
<td>95</td>
</tr>
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<td>TESSAOUA</td>
<td>24-Jun</td>
<td>84</td>
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<td>TILLABERY</td>
<td>29-Jun</td>
<td>88</td>
</tr>
<tr>
<td>TORODI AGRI</td>
<td>02-Jun</td>
<td>111</td>
</tr>
<tr>
<td>ZINDER AERO</td>
<td>26-Jun</td>
<td>81</td>
</tr>
</tbody>
</table>

Elaborations obtenues par le Système CeSIA à la DNN, Niamey, sur la base des données pluvimétriques de 60 postes au Niger; données disponibles jusqu’au 20 Juillet 1993. Le longueur de saison indiqué a une variabilité de plus ou moins 5 jours.

Figure 1. Onset of growing season. Example of decadal agrometeorological bulletin.
The Millet Simulation Model

The most important aspects in the growing season of millet in the Sahelian region are the timing of the onset of the rain season (and therefore the sowing date, which can be early, normal, or late, compared with crop requirements for the normal development of cycle), distribution of rainfall in the following months, water balance in the most sensitive phases of crop growth, and effective length of the growing season. Based on these criteria, a simple model of crop development has been developed to evaluate crop conditions during the season, based on daily rainfall data in any 10-day period at the Meteorological Service of Niamey (Figure 2).

Figure 2. Flow chart of the model.

Once the meteorological stations to be used are determined, the model can simulate millet varieties with different cycle length (75, 90, 120 days); the sowing date can be assigned by the user or detected by the program on the basis of a rainfall threshold defined by the user. Yield reductions (compared with a no-water limited potential production) are calculated as a function of the delay of the sowing date and of the potential water balance. Differences in millet sensitivity to water stress during its cycle are taken into account by three reduction functions for the three main phenological phases: growing period (the less sensitive one), flowering (the most sensitive one), and grain filling. The cumulative
effect of more than one stress during the crop cycle is multiplied by the potential crop yield of the area to obtain the estimated actual yield.

After looking for the first sowing date, the program evaluates rainfall distribution in the following days to verify conditions for germination and crop establishment. If not enough rain will follow seeding, then a new sowing date has to be detected. In the case of long cycle varieties, if a delay in the sowing date makes the growing period before the end of the rain season too short, a first reduction coefficient is calculated.

During the crop cycle, three coefficients will be calculated if a water stress will be experienced by the crop. Water balance is simply based on climatic evapotranspiration and daily rainfall records of each station. Final average yield for each administrative unit is quantified using historical records provided by the Statistical Service of the Ministry of Agriculture.

Figure 3 shows the parameterization of crop phenology. All model outputs can be easily processed to produce graphical representations like that shown in Figure 4, using results

<table>
<thead>
<tr>
<th>Varieties</th>
<th>Phase length</th>
<th>Initial Kc</th>
<th>Growth at five-day interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 days</td>
<td>Growing 50</td>
<td>0.2</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>Flowering 15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90 days</td>
<td>15</td>
<td>0.15</td>
<td>0.06538</td>
</tr>
<tr>
<td>120 days</td>
<td>15</td>
<td>0.1</td>
<td>0.0562</td>
</tr>
<tr>
<td>phot.</td>
<td>20</td>
<td>0.1</td>
<td>(1-0.1)(IPFL-IPSEM)</td>
</tr>
<tr>
<td>120 days</td>
<td>JFL - JSEM</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Parameterization of crop phenology.

![Graphical representation of crop phenology model output](image)

Figure 4. Graphical representation of crop phenology model output.

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obtained at the station level. Applied to several years of data, the model allows a classification like the one shown in Figure 5, where suitability classes are expressed as the ratio of an estimated yield attained under water-limited conditions and a theoretical maximum yield attainable under non-water-limited management.

**Figure 5. Classes of land productivity.**

**Satellite Image Analyses**

A strong relation exists in CILSS countries between national meteorological services and the AGRHYMET Center; because of this, for satellite-based analyses, SISP is actually using decadal images of NDVI produced by AGRHYMET and regularly distributed to each country. Based on IDRISI (a GIS provided to CILSS countries by the United States in cooperation with the AGRHYMET Program), a number of procedures have been developed in order to extract temporal profiles of NDVI for relevant sites detected in different zones of the country. This approach was tested in 1993. Fifteen sites were identified in the Department of Tillabery and monitored during the whole season.

Phenological and field measurements were taken for millet crop, and temporal profiles of NDVI were extracted from the seasonal series of images provided by AGRHYMET. The same processing was applied to images in 1991 and 1992. Figure 6 shows temporal profiles of the cropped test sites of Say with natural vegetation.

In the graph in Figure 7, observed phenological phases on the cropped test site are emphasized for comparison with NDVI shape and with development simulated by the model during the same season on the basis of rainfall data. Phenological observations were strongly correlated with NDVI evolution in all test sites and it was confirmed that flowering corresponds to the maximum value that NDVI reaches during the growing season. The regression between measured yields and maximum seasonal NDVI of each site shows that NDVI explains more than 87% of yield measured in the 15 sites.
Figure 6. Growing season in Say, Niger, 1993.

Figure 7. Crop development as simulated by CeSIA model.

The graphic interface of the system allows the operator to overlay the outputs of the different modules and integrate them for the production of maps, graphs, and tables. The national meteorological service and the national early warning units usually use these products.

Although AGRHYMET is not yet regularly providing MeteoSat images to CILSS countries, similar procedures are being developed for the evaluation of sowing dates based on MeteoSat images of estimated rainfall. These procedures will be developed and tested to make them operational in the future for meteorological services.
Syntheses of analysis results are regularly published in the decadal agrometeorological bulletin of the National Meteorological Service of Niger, including crop yield forecasting toward the end of the growing season.

Application to Other Countries

For the last few years, we have been studying the possibility of extending the application of SISP to other countries. Few difficulties exist for its application in other meteorological services of CILSS countries, where the AGRHYMET Program has already improved the meteorological network and database, thanks to the modular structure of SISP. Its application to other Sahelian countries requires some preliminary information. This is necessary to adapt the model to the agrometeorological characteristics of each country.

These data are already available for some countries, and at least some of the necessary information is available for other countries.

A lot of information is available at the AGRHYMET Regional Center of Niamey and the national meteorological service of each country.

The necessary data for extending SISP to other countries are:

- Pluviometric database (Climbase.dbf)
- Evapotranspiration database (decadal values)
- Documentation of pluviometric stations
- Statistical data on agricultural yields for each administrative unit
- Vector files of administrative boundaries at national and subnational levels for result spatialization

Some preliminary analyses are also necessary. These are useful for the characterization of the territory, which is necessary to determine the agroclimatic zone for each station and for the correct interpretation of model results. The preliminary elaborations required are:

- Attribution of each pluviometric station to its reference synoptic station
- Creation of a reference file for each administrative unit for agricultural statistics (*.ref.dat)
- Agroclimatic characterization of the country for the attribution of millet crop variety to each station

Conclusions

The system has a modular structure and an easy user interface to provide national meteorological services with a simple methodology for agroclimatic characterizations, season monitoring, crop growth assessment, and yield forecasting, based on the most common and easily obtainable agrometeorological parameters. The system does not pretend to provide the user with all possible facilities needed in early warning and monitoring systems for agriculture; it represents an easy user shell that can be easily enriched with new modules. It actually integrates different approaches and provides the agrometeorologist with a number of useful working tools.
The research activities carried out in Niger in the past few years and the collaboration with and experience of the Niger meteorological service are important to the development of such an operational system. For these reasons, all module outputs have been oriented to integrate and complete information to be included in the agrometeorological bulletins edited by national meteorological services and early warning systems.

Some of the most important limitations of the system are that the field of application is limited to millet crop and that phenological data and information about local varieties has been collected mainly for Niger. Although similar cultural systems exist in the other Sahelian countries, application of SISP in other regions should require recovering existing experiences and knowledge on millet local ecotypes. The application of the approach to other crops requires a deeper evaluation of crop requirements and main limiting environmental factors. On the other side, the statistical approach and image analysis procedures are more easily applicable to other arid and semi-arid regions.

**Further Reading**


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Reference Evapotranspiration and Crop Coefficients

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Abstract

During recent decades, automated agricultural weather networks have become quite common in the United States and throughout the world. The purpose for these networks varies tremendously, but one of the most common reasons for developing agricultural weather networks is to provide information on evapotranspiration to government agencies, water purveyors, and farmers. Because of great diversity in crops, cropping seasons, and irrigation management, it is nearly impossible to widely disseminate crop specific evapotranspiration information. Therefore, most weather networks provide only reference evapotranspiration and they facilitate the use of crop coefficient information to estimate site-specific crop evapotranspiration rates. In this chapter, methods to estimate reference evapotranspiration are provided for both a short grass and a tall alfalfa reference crop. In addition, new methods to refine crop coefficients to improve crop evapotranspiration estimates are discussed. These new approaches include improving the estimates of off-season evapotranspiration and the initial crop coefficient during the season. Other items discussed include refinements to midseason crop coefficients, accounting for irrigation frequency during early growth, adjusting for immature orchards and vineyards, and accounting for cover crop contributions to evapotranspiration.

Reference Crop Evapotranspiration

The American Society of Civil Engineers (ASCE) Committee on Evapotranspiration in Irrigation and Hydrology has met several times during the past year to discuss standardization of the equations used to estimate reference crop evapotranspiration. A report on these meetings was completed and sent to the ASCE in January 2000. In this report, the committee recommended that two crops be adopted as approximations for reference crop evapotranspiration ($ET_{o,r}$). The symbols and definitions given are:

$ET_o$—Reference ET for a short crop having an approximate height of 0.12 m (similar to grass).

$ET_r$—Reference ET for a tall crop having an approximate height of 0.50 m (similar to alfalfa)

For estimating $ET_{ref}$, a modified version of the Penman-Monteith equation (Allen et al., 1999) with some fixed parameters was recommended (Walter et al., 2000; Itenfisu et al., 2000). The equation is

$$ET_{ref} = \frac{0.408 \Delta (R_n - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + C_d u_2)}$$

(1)
where $\Delta$ is the slope of the saturation vapor pressure at mean air temperature curve (kPa °C$^{-1}$), $R_n$ and $G$ are the net radiation and soil heat flux density in MJ m$^{-2}$d$^{-1}$ for daily or MJ m$^{-2}$h$^{-1}$ for hourly data, $\gamma$ is the psychrometric constant (kPa °C$^{-1}$), $T$ is the daily or hourly mean temperature (°C), $u_a$ is the mean wind speed in m s$^{-1}$, and $e_a - e_s$ is the vapor pressure deficit (kPa). In Eq. 1, the coefficients in the numerator ($C_n$) and the denominator ($C_d$) are given specific values depending on the calculation time step and the reference crop as shown in Table 1. The values for $C_n$ vary because the aerodynamic resistance is different for the two reference crops and because of the conversion from energy to depth of water units.

Table 1. Coefficients used in the $ET_{\text{ref}}$ equation for a short 0.12 m tall canopy ($ET_o$) and for a 0.50 m tall canopy ($ET_r$).

<table>
<thead>
<tr>
<th>Calculation time step</th>
<th>$ET_o$</th>
<th>$ET_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_n$</td>
<td>$C_d$</td>
</tr>
<tr>
<td>Daily or monthly</td>
<td>900</td>
<td>0.34</td>
</tr>
<tr>
<td>Hourly during daytime</td>
<td>37</td>
<td>0.24</td>
</tr>
<tr>
<td>Hourly during nighttime</td>
<td>37</td>
<td>0.96</td>
</tr>
</tbody>
</table>

The output units from Eq. 1 are in mm d$^{-1}$ for the daily or monthly calculations and in mm h$^{-1}$ for the hourly time step. For the daily data, $R_n$ is input in MJ m$^{-2}$d$^{-1}$ and $G$ is assumed to be zero. For the hourly calculations, $G$ is assumed equal to 10% of $R_n$ when $R_n \geq 0$ and $G$ is assumed equal to 50% of $R_n$ for $R_n < 0$. In addition, the surface (canopy) resistance is set equal to 50 s m$^{-1}$ during daytime and to 200 s m$^{-1}$ at night. This change accounts for nighttime stomatal closure and improves the daytime estimates as well (Figure 1).

![Figure 1. A plot of $ET_o$ estimated using the Penman-Monteith equation with measured $R_n$, $G$, $e_a - e_s$, and $u_a$ assuming a canopy resistance of 50 s m$^{-1}$ versus daytime, half-hour lysimeter measurements of $ET_o$.](image)
Crop Coefficients

While reference crop evapotranspiration accounts for variations in weather and offers a measure of the “evaporative demand” of the atmosphere, crop coefficients account for the difference between the crop evapotranspiration (ET) and ET₀. The ASCE committee has recommended the use of Kᵅ and Kᵢ for crop coefficients relative to ET₀ and ETᵣ, respectively (Walter et al., 2000).

The main factors affecting the difference between ETᵣ and ET₀ are (1) light absorption by the canopy, (2) canopy roughness, which affects turbulence, (3) crop physiology, (4) leaf age, and (5) surface wetness. Because evapotranspiration (ET) is the sum of evaporation (E) from soil and plant surfaces and transpiration (T), which is vaporization that occurs inside of the plant leaves, it is often best to consider the two components separately. When not limited by water availability, both transpiration and evaporation are limited by the availability of energy to vaporize water. Therefore, solar radiation (or light) interception by the foliage and soil have a big effect on the ET rate.

As a crop canopy develops, the ratio of T to ET increases until most of the ET comes from T and E is a minor component. This occurs because the light interception by the foliage increases until most light is intercepted before it reaches the soil. Therefore, crop coefficients for field and row crops generally increase until the canopy ground cover reaches about 75% and the light interception is near 80%. For tree and vine crops, the peak Kᵅ is reached when the canopy has reached about 62% ground cover. The difference between the crop types results because the light interception is higher for the taller crops.

During the off season and early during crop growth, E is the main component of ET. Therefore, a good estimate of the Kᵅ for bare soil is useful to estimate off-season soil evaporation and ETᵣ early in the season.

Bare Soil Kᵅ Values

A two-stage method for estimating soil evaporation presented by Stroonsnjider (1987) is used to estimate bare soil crop coefficients. In stage 1, the soil evaporation rate is limited only by energy availability to vaporize water. In stage 2, the soil has dried sufficiently that soil hydraulic properties limit the transfer of water to the surface for vaporization. The method requires a maximum crop coefficient for soil evaporation (Kₓᵅ). The Kₓᵅ is estimated using

\[ Kₓᵅ = 1.05 - 0.03ET₀ \]  \hspace{1cm} (2)

During stage 1 evaporation, the cumulative soil evaporation (CEₛ) is calculated as

\[ CEₛ = Kₓᵅ CET₀ \]  \hspace{1cm} (3)

During stage 2, the cumulative soil evaporation is calculated as the product of a soil-specific hydraulic parameter (β) and the square root of the product of Kₓᵅ and CET₀.

\[ CEₛ = \beta \sqrt{Kₓᵅ CET₀} \]  \hspace{1cm} (4)
Figure 2 illustrates the method used to determine $\beta$. Actually, $\beta$ is the value of $\sqrt{K_{\infty}CET_0}$ where the measured $CE_s$ separates from the plot of $K_{\infty}CET_0$ versus $\sqrt{K_{\infty}CET_0}$. In addition, $\beta$ is the slope of the linear regression of $CE_s$ versus $\sqrt{K_{\infty}CET_0}$ for all data pairs where $\sqrt{K_{\infty}CET_0} > \beta$.

\[ y = 4.11x \]
\[ R^2 = 0.98 \]

Figure 2. Plot of measured cumulative soil evaporation ($CE_s$) versus the square root of the product of the maximum soil crop coefficient ($K_{\infty}$) and cumulative $ET_o$ ($CET_o$). The dashed line is the linear regression of all data points where the x-value is greater than 4.11.

For a fixed mean $ET_o$ rate, the $CE_s$ from one soil wetting to the next is estimated as the product of $K_{\infty}$ and $CET_o$ during stage 1 and as $\beta\sqrt{K_{\infty}CET_o}$ during stage 2 evaporation. Here, $CET_o$ equals the product of the mean $ET_o$ and the number of days between wetting. An example of the $K_{\infty}$ calculations as a function of wetting frequency and the mean $ET_o$ rate is shown in Figure 3 for a $\beta = 2.6$. The $\beta = 2.6$ was used because the results approximate the widely used $K_{\infty}$ values for initial growth (Doorenbos and Pruit, 1977).

The soil evaporation model is used to estimate crop coefficients for bare soil using the daily mean $ET_o$ rate and the expected number of days between significant precipitation ($P_s$) on each day of the year. Daily precipitation is considered significant when $P_s > 3$ $ET_o$. A sample $K_{\infty}$ curve for bare soil evaporation near Fresno, California, is shown in Figure 4. The daily mean $ET_o$ rates for each day of the season were computed using a cubic spline fit through the monthly means calculated from 11 years of weather data. Then the daily $K_{\infty}$ values for bare soil were computed using the product of the daily $ET_o$ rate and the days between rainfall to determine $CET_o$ and Eqs. 2, 3, and 4 with $\beta = 2.6$. This provides a baseline crop coefficient curve for the off season.
Figure 3. Crop coefficient ($K_c$) values for bare or near-bare soil as a function of mean $ET_o$ rate and wetting frequency in days by significant rainfall or irrigation using a soil hydraulic factor $\beta = 2.6$.

Figure 4. A plot of the annual crop coefficient curve for bare soil for Fresno, California, based on mean daily $ET_o$ rate and days between significant precipitation ($P_r$).
Field and Row Crop $K_c$ Values

Crop coefficients for field and row crops are calculated using a method similar to that described by Doorenbos and Pruitt (1977). In their method, the season is separated into initial (date A–B), rapid (date B–C), midseason (date C–D), and late season (date D–E) growth periods (Figure 5). During initial growth and midseason, the $K_{co}$ values are initially fixed at $K_{c1}$ and $K_{c2}$, respectively. During the rapid growth period, when the canopy increases from about 10% to 75% ground cover, the $K_{co}$ value increases linearly from $K_{c1}$ to $K_{c2}$. During late season, the $K_{co}$ decreases linearly from $K_{c2}$ to $K_{c3}$ at the end of the season.

![Crop Coefficient ($K_{co}$) Curve](image)

**Figure 5. Hypothetical crop coefficient ($K_{co}$) curve for typical field and row crops showing the growth stages and percentages of the season from planting to critical growth dates.**

In Doorenbos and Pruitt (1977), estimated numbers of days for each of the four periods were provided to help identify the end dates of growth periods. However, because there are variety differences and because it is difficult to visualize when the inflection points occur, irrigators often find this confusing. To simplify this problem, percentages of the season from planting to each inflection point rather than days in growth periods are used. Irrigation planners need only enter the planting and end dates, and the intermediate dates are determined from the percentages, which are easily stored in a computer program.

Initially, $K_{c1}$ is determined by using the mean $ET_o$ irrigation frequency, and Eqs. 2, 3, and 4 to calculate $K_{co}$ for bare soil evaporation during the initial growth period. However, the daily $K_{co}$ values for bare soil, based on rainfall frequency, are used if they are bigger than $K_{c1}$.

The values for $K_{c2}$ and $K_{c3}$ depend on the difference in (1) $R_n-G$, (2) crop morphology effects on turbulence, and (3) physiological differences between the crop and reference crop. Sample $K_{c2}$ and $K_{c3}$ values for crops grown in a region with $4.0 \leq ET_o \leq 7.0$ mm d$^{-1}$ are given in Table 2. In general, for environments with $ET_o < 4.0$, $K_{co}$ values are closer to

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Table 2. Crop coefficients (i.e., $K_{cl}$ for dates C-D and $K_{c2}$ for date E) and percentages of the season from planting until the indicated growth dates for field and row crops. Growth dates A, B, C, D, and E area as shown in Figure 5.

<table>
<thead>
<tr>
<th>Crop</th>
<th>% of season until date</th>
<th>Crop coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>Alfalfa (cycle)</td>
<td>7</td>
<td>30</td>
</tr>
<tr>
<td>Alfalfa (averaged)</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>Artichokes</td>
<td>6</td>
<td>19</td>
</tr>
<tr>
<td>Asparagus</td>
<td>12</td>
<td>25</td>
</tr>
<tr>
<td>Barley</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Beans (pinto)</td>
<td>24</td>
<td>40</td>
</tr>
<tr>
<td>Beans (dry)</td>
<td>24</td>
<td>40</td>
</tr>
<tr>
<td>Beans (green)</td>
<td>22</td>
<td>56</td>
</tr>
<tr>
<td>Beets (table)</td>
<td>25</td>
<td>60</td>
</tr>
<tr>
<td>Broccoli</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>Carrots</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>Celery</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>Cereal Grains</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Corn (grain)</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Corn (silage)</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Cotton</td>
<td>20</td>
<td>55</td>
</tr>
<tr>
<td>Crucifers</td>
<td>25</td>
<td>63</td>
</tr>
<tr>
<td>Cucumber</td>
<td>19</td>
<td>47</td>
</tr>
<tr>
<td>Eggplant</td>
<td>23</td>
<td>54</td>
</tr>
<tr>
<td>Lentil</td>
<td>13</td>
<td>33</td>
</tr>
<tr>
<td>Lettuce</td>
<td>25</td>
<td>65</td>
</tr>
<tr>
<td>Melon</td>
<td>21</td>
<td>50</td>
</tr>
<tr>
<td>Millet</td>
<td>14</td>
<td>36</td>
</tr>
<tr>
<td>Oats</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Onion (dry)</td>
<td>10</td>
<td>26</td>
</tr>
<tr>
<td>Onion (green)</td>
<td>25</td>
<td>70</td>
</tr>
<tr>
<td>Peas</td>
<td>20</td>
<td>47</td>
</tr>
<tr>
<td>Peppers</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Potato</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Radishes</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Rice</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>Safflower</td>
<td>17</td>
<td>45</td>
</tr>
<tr>
<td>Sorghum</td>
<td>16</td>
<td>42</td>
</tr>
<tr>
<td>Spinach</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>Squash</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>Strawberries w/mulch</td>
<td>15</td>
<td>45</td>
</tr>
<tr>
<td>Sugarbeet</td>
<td>15</td>
<td>45</td>
</tr>
<tr>
<td>Sunflower</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Tomato</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>Wheat</td>
<td>20</td>
<td>45</td>
</tr>
</tbody>
</table>
\( K_c = 1.00 \) (i.e., \( K_{co} \) values increase when \( K_{co} < 1.00 \) and decrease when \( K_{co} > 1.00 \) when the evaporative demand is less). For example, the \( K_c \) for citrus is higher in a low than a high evaporative demand climate. This most likely results from differences in soil evaporation and possibly water stress. When \( ET_o > 7.0 \) mm d\(^{-1}\), \( K_c \) values are farther from \( K_c = 1.00 \) (i.e., \( K_{co} \) values decrease when \( K_{co} < 1.00 \) and increase when \( K_{co} > 1.00 \) when the evaporative demand is higher). For example, alfalfa may have a \( K_{c1} = 1.05 \) in a climate with \( ET_o \approx 5.0 \) mm d\(^{-1}\) or a \( K_{c2} = 1.15 \) in a climate with \( ET_o \approx 9.0 \) mm d\(^{-1}\).

A sample \( K_{co} \) curve for cotton grown near Fresno, California, is shown in Figure 6. Cotton is not typically irrigated during initial growth, so the value for \( K_{c1} \) was determined using the mean \( ET_o \) during the period. The irrigation frequency was 30 days and \( \beta = 2.6 \). However, the resulting \( K_{co} \) was smaller than the \( K_{co} \) for bare soil evaporation early in the period, so the \( K_{co} \) during initial growth partially follows the bare soil curve. If irrigated with greater frequency, the \( K_{c1} \) would likely be higher than the bare soil crop coefficient, and it would be constant during the initial period.

![Crop coefficient curve](image)

Figure 6. Crop coefficient curve, using a 30-day irrigation frequency during initial growth, for cotton grown near Fresno, California (solid line). Crop coefficient curve for bare soil (dotted line).

Some field crops are harvested before senescence and there is no late season drop in \( K_{co} \) (e.g., silage corn and fresh market tomatoes). Fixed annual \( K_{co} \) values are possible for some crops (e.g., turfgrass and pasture) with little loss in accuracy.

**Deciduous Tree and Vine Crop \( K_c \) Values**

Deciduous tree and vine crops, without a cover crop, have similar \( K_{co} \) curves but without the initial growth period (Figure 7). The season begins with rapid growth at leaf out when the \( K_{co} \) increases from \( K_{c1} \) to \( K_{c2} \). The midseason period begins at approximately 62% ground cover. Then, unless the crop is immature, the \( K_{co} \) is fixed at \( K_{c2} \) until the onset of senescence. During late season, the \( K_{co} \) decreases from \( K_{c2} \) to \( K_{c3} \), which occurs at about leaf drop or when the transpiration is near zero.
Figure 7. Hypothetical crop coefficient ($K_c$) curve for typical deciduous orchard and vine crops, showing the growth stages and percentages of the season from leaf out to critical growth dates.

At leaf out, $K_{c_1}$ is set equal to that of the bare soil evaporation on that date based on $ET_o$ and rainfall frequency. The assumption is that the $ET_o$ for a deciduous orchard or vineyard at leaf out should be about equal to the bare soil evaporation. The $K_{c_2}$ and $K_{c_3}$ values again depend on $(R_{s} - G)$, canopy morphology effects on turbulence, and plant physiology differences between the crop and reference crop. Some sample $K_{c_2}$ and $K_{c_3}$ values for trees and vines are given in Table 3.

Table 3. Crop coefficients (i.e., $K_{c_2}$ for dates C–D and $K_{c_3}$ for date E) and percentages of the season from leaf out until the indicated growth date inflection points for major tree and vine crops. Growth dates B, C, D, and E are as shown in Figure 7.

<table>
<thead>
<tr>
<th>Crop</th>
<th>% of season until date</th>
<th>Crop coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>Grapevines</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>Stone fruits</td>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td>Apple</td>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td>Kiwifruit</td>
<td>22</td>
<td>67</td>
</tr>
<tr>
<td>Citrus</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>Citrus (desert)</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>Olives</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>Avocado</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>Evergreen</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>Almonds</td>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td>Walnuts</td>
<td>50</td>
<td>75</td>
</tr>
</tbody>
</table>
With a cover crop, the $K_{co}$ values for deciduous trees and vines are increased depending on the amount of cover. In general, adding 0.35 to the in-season, no-cover $K_c$ for a mature crop, but not to exceed 1.15, is recommended. With immature crops, adding more than 0.35 may be required. For a cover crop during the off-season, adding 0.35 to the bare soil $K_{co}$, but not exceeding 0.90, is recommended. During the off-season, a $K_{co} \leq 0.90$ is used because shading by the trunks and branches is assumed to reduce the cover crop $ET$ slightly below $ET_c$. The $K_{co}$ curve for a stone fruit orchard is shown in Figure 8. The dashed line is for a mature orchard with a cover crop and the solid line is for a clean cultivated orchard.

![Diagram of crop coefficient curve for a stone fruit orchard in Fresno, California. The solid line is for a clean cultivated orchard and the dashed line is for an orchard with green growing cover crop contributing a maximum of 0.35 above the clean cultivated $K_{co}$. The dotted line is for bare soil evaporation. The $K_{co}$ cannot exceed 1.15 during the cropping season and cannot exceed 0.90 during the off-season unless the soil evaporation exceeds 0.90.](image)

Figure 8. Crop coefficient curve for a stone fruit orchard grown near Fresno, California. The solid line is for a clean cultivated orchard and the dashed line is for an orchard with a green growing cover crop contributing a maximum of 0.35 above the clean cultivated $K_{co}$. The dotted line is for bare soil evaporation. The $K_{co}$ cannot exceed 1.15 during the cropping season and cannot exceed 0.90 during the off-season unless the soil evaporation exceeds 0.90.

Immature deciduous tree and vine crops use less water than mature crops. The following equation is used to adjust the mature $K_{co}$ values ($K_{cm}$) as a function of percentage ground cover ($C_g$).

$$\text{If } \sin \left( \frac{\pi C_g}{140} \right) \geq 1.0 \text{ then } K_{co} = K_{cm} \text{ else } K_{co} = K_{cm} \left[ \sin \left( \frac{\pi C_g}{140} \right) \right]$$

(5)

A sample $K_{co}$ curve for an immature stone fruit orchard having $C_g = 35\%$ and $C_g = 40\%$ at the beginning and end of midseason, respectively, is represented by the solid $K_{co}$ line in Figure 9. The dashed curve is for a mature, clean-cultivated tree crop.
Figure 9. Crop coefficient curve for a stone fruit orchard grown near Fresno, California. The dashed line is for a clean cultivated, mature orchard and the solid line is for an immature orchard having $C_g = 35\%$ and $C_g = 40\%$ at the beginning and end of the midseason period. The dotted line is for bare soil evaporation.

Subtropical Orchards

For mature subtropical orchards (e.g., citrus), using a fixed $K_{co}$ during the season provides acceptable $ET_o$ estimates. However, if higher, the bare soil $K_{co}$ is used for the orchard $K_{co}$. The solid line in Figure 10 represents the $K_{co}$ curve for a mature citrus orchard grown near Fresno. For an immature orchard, the mature $K_{co}$ values ($K_{cm}$) are adjusted for their percentage ground cover ($C_g$) using the following criteria.

$$\text{If } \sqrt{\sin \left( \frac{\pi C_g}{140} \right)} \geq 1.0 \text{ then } K_{co} = K_{cm} \text{ or else } K_{co} = K_{cm} \sqrt{\sin \left( \frac{\pi C_g}{140} \right)}$$  \hspace{1cm} (6)

The $K_{co}$ curve (dashed line) for immature orchards for $C_g = 25\%$, 30\%, 35\%, and 40\% on January 1, May 1, September 1, and December 31, respectively, is also shown in Figure 10.

Conclusions

The ASCE–ET Task Committee on Standardization of Reference Evapotranspiration recently adopted a modified Penman-Monteith equation for use in estimating reference evapotranspiration. The equation and coefficients for calculating both 0.10 m and 0.50 m reference crops were presented in this chapter. In addition, new methods to refine crop coefficient ($K_{co}$) values for improved crop evapotranspiration estimates were discussed. The new approach uses an estimate of off-season, bare soil crop coefficients based on daily mean $ET_o$ rates and rainfall frequency to identify a lower limit for $K_{co}$ values. Other
Figure 10. Crop coefficient curve for a citrus orchard grown near Fresno, California. The solid line is for a clean cultivated, mature orchard and the dashed line is for an immature orchard having $C_k = 25\%$, $30\%$, $35\%$, and $40\%$ on January 1, May 1, September 1, and December 31, respectively. When higher, the $K_{co}$ is set equal to the bare soil $K_{co}$ (dotted line).

The items discussed include midseason and end-of-season crop coefficients, accounting for irrigation frequency during initial growth, adjusting for immature orchards and vineyards, and accounting for cover crop contributions to evapotranspiration. The information presented can be used in a computer program to derive improved estimates of crop evapotranspiration that account for a wide variety of environmental and biological factors.

**Acknowledgments**

I want to acknowledge the ASCE–ET Task Committee on Standardization of Reference Evapotranspiration, which developed the recommendation for $ET_{ref}$, and the ASCE Irrigation and Drainage Council of the Environmental and Water Resources Institute (EWRI), which sanctioned the Committee. Members of the Committee include: I.A. Walter (Chairman), R.G. Allen (Vice Chairman), M.E. Jensen (secretary), R.L. Elliott (Chairman ASCE–ET), P.W. Brown, R.H. Cuenca, S. Eching, M.J. Hattendorf, T.A. Howell, D.J. Hunsaker, D. Itenfisu, D.L. Martin, B. Mecham, R.L. Snyder, T.L. Spofford, J.L. Wright, and B. Clemmens (EWRI).

**References**


Soil Moisture Monitoring and Modeling in the Great Plains

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High Plains Regional Climate Center, University of Nebraska, Lincoln

Abstract
Availability of soil moisture is an essential determinant of healthy growth of crops and yield. Thus, daily measurement of soil moisture allows farmers to prepare for various water-related stress mitigating activities, including irrigation scheduling. Furthermore, daily measurement of soil moisture provides opportunities for various hydrological and boundary layer meteorological studies, including energy flux estimation, model validation, and flood forecasting.

This paper presents various aspects of an ongoing project of soil moisture measurement network establishment over the northern Great Plains. This project is sponsored by the High Plains Regional Climate Center (HPRCC) and is part of an automated weather data network (AWDN) that is a collaborative effort between the state climate offices and HPCC. This study discusses instrumentation of the soil moisture network and the accuracy/limitations of the measured data. Moreover, a soil water balance model is applied for a soil moisture measurement site to determine soil moisture and energy partitioning under two hydrologically different years and under three types of crop cover and management conditions.

The Network, Calibration of Sensors, and Sensor Performance
Fourteen AWDN stations in Nebraska are currently participating in the soil moisture network (Figure 1). Soil moisture probes have been part of these stations since 1998. Before the field installation, two types of soil moisture measuring probes were calibrated and tested under field and greenhouse conditions. These probes are Hydra and CS615. This chapter presents results from the greenhouse experiments.

Figure 1. Location of soil moisture measuring probes in Nebraska.
Under field conditions, the top 30 cm zone in the soil profile experiences most of the fluctuation in soil water content because of precipitation recharge and evapotranspiration depletion. As a result, we have selected two buckets, each 35 cm high, and assumed that they resemble field condition soil profile when filled with soil. Moreover, two sets of CS615 and Hydra probes were included for each of the buckets. Before filling the buckets with soil and placing the instruments, the buckets were perforated with 3 mm holes with 2-by-2 cm spacing. Then they were filled with soil up to the 19 cm line. Well-mixed silty clay soil was packed uniformly during filling to maintain homogeneous bulk density throughout the profile. When the buckets were filled up to the 19 cm line, a pair of Hydra probes was inserted vertically on the opposite side of each bucket. The placement of the Hydra probes was halfway between the bucket’s edge and the geometric center. Subsequently, the buckets were filled up to 32 cm line. At this time, two CS615 probes were fully inserted in each bucket. Again, they were located at the midpoint between the edge and center of the buckets and equally spaced from Hydra probe locations. Finally, the soils of the two buckets were completely saturated over a 48-hour period.

Data collection started 2 days after the last application of water for homogeneous saturation of the soil. Data for every 30 minutes for both types of sensors were recorded in the data logger. Subsequently, a daily average was calculated from the 48 readings each day. The buckets were weighed each day around 4:00–5:00 PM to record soil water content changes. Volumetric soil water content for the whole bucket was estimated by using the weights recorded and soil bulk density. Each of the four sensors was compared to and calibrated against the volumetric water contents calculated from daily weight changes and soil bulk density. Table 1 presents the statistical analysis of performance of the instruments after calibration. The CS615 provided better overall performance, but both sensor types gave satisfactory performance.

Table 1a. Relationship between sensor estimated and actual volumetric water content: bucket 1.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>R-squared</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydra A</td>
<td>0.9166</td>
<td>0.0228</td>
</tr>
<tr>
<td>Hydra B</td>
<td>0.8898</td>
<td>0.0261</td>
</tr>
<tr>
<td>CS615A</td>
<td>0.9588</td>
<td>0.0181</td>
</tr>
<tr>
<td>CS615B</td>
<td>0.9357</td>
<td>0.0155</td>
</tr>
</tbody>
</table>

Table 1b. Relationship between sensor estimated and actual volumetric water content: bucket 2.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>R-squared</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydra C</td>
<td>0.8483</td>
<td>0.0271</td>
</tr>
<tr>
<td>Hydra D</td>
<td>0.8600</td>
<td>0.0267</td>
</tr>
<tr>
<td>CS615C</td>
<td>0.9521</td>
<td>0.0153</td>
</tr>
<tr>
<td>CS615D</td>
<td>0.9386</td>
<td>0.0173</td>
</tr>
</tbody>
</table>
Further comparison of calibrated sensor readings and gravimetric determination indicates that CS615 estimates contain less variability in the data (Table 2a and 2b). Correlation estimates were calculated for inter- and intra-brand measurements (Table 3a and 3b) to further determine the performance of the sensors. The correlation estimates are very high for both inter- and intra-brand measurements. Moreover, in some cases, inter-brand correlations are higher than intra-brand correlation estimates (Table 3a). Overall, the results suggest that consistency and interchangeability is higher within a brand than between brands. On the other hand, because there are high correlation estimates for all cases, it can also be suggested that interchangeability between these two brands is acceptable.

The sensors were also calibrated and tested under field conditions. The sensor measurements were satisfactory (not shown here). Finally, the AWDN network installed Hydra probes for soil water measurement and monitoring. Currently, the hydra probes are placed at 10 cm, 25 cm, 50 cm, and 100 cm under the surface at each soil water monitoring site. The Hydra probes were provided by the Natural Resources Conservation Service (NRCS) under a collaborative project. The measured soil moisture is currently being used to validate a soil water model that helps to devise irrigation scheduling for selected farmers.

**Table 2a. Statistics for the difference between calibrated sensors and gravimetric determinations: bucket 1.**

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Mean</th>
<th>Std</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydra A</td>
<td>0.017</td>
<td>2.2639</td>
<td>0.300</td>
</tr>
<tr>
<td>Hydra B</td>
<td>-0.011</td>
<td>2.5822</td>
<td>0.342</td>
</tr>
<tr>
<td>CS615A</td>
<td>0.004</td>
<td>1.7996</td>
<td>0.238</td>
</tr>
<tr>
<td>CS615B</td>
<td>0.001</td>
<td>1.5420</td>
<td>0.204</td>
</tr>
</tbody>
</table>

**Table 2b. Statistics for the difference between calibrated sensors and gravimetric determinations: bucket 2.**

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Mean</th>
<th>Std</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydra C</td>
<td>-0.222</td>
<td>2.6891</td>
<td>0.356</td>
</tr>
<tr>
<td>Hydra D</td>
<td>0.0001</td>
<td>2.5838</td>
<td>0.342</td>
</tr>
<tr>
<td>CS615C</td>
<td>0.0052</td>
<td>1.7104</td>
<td>0.226</td>
</tr>
<tr>
<td>CS615D</td>
<td>-0.003</td>
<td>1.5117</td>
<td>0.200</td>
</tr>
</tbody>
</table>
Table 3a. Correlation between sensor estimates: bucket 1.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Hydra A</th>
<th>Hydra B</th>
<th>CS615A</th>
<th>CS615B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydra A</td>
<td>1.000</td>
<td>0.998</td>
<td>0.962</td>
<td>0.986</td>
</tr>
<tr>
<td>Hydra B</td>
<td>0.998</td>
<td>1.000</td>
<td>0.945</td>
<td>0.974</td>
</tr>
<tr>
<td>CS615A</td>
<td>0.962</td>
<td>0.945</td>
<td>1.000</td>
<td>0.991</td>
</tr>
<tr>
<td>CS615B</td>
<td>0.986</td>
<td>0.974</td>
<td>0.991</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Table 3b. Correlation between sensor estimates: bucket 2.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Hydra C</th>
<th>Hydra D</th>
<th>CS615C</th>
<th>CS615D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydra C</td>
<td>1.000</td>
<td>0.999</td>
<td>0.943</td>
<td>0.941</td>
</tr>
<tr>
<td>Hydra D</td>
<td>0.999</td>
<td>1.000</td>
<td>0.948</td>
<td>0.946</td>
</tr>
<tr>
<td>CS615C</td>
<td>0.943</td>
<td>0.948</td>
<td>1.000</td>
<td>0.998</td>
</tr>
<tr>
<td>CS615D</td>
<td>0.941</td>
<td>0.946</td>
<td>0.998</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Soil Water Model and Its Applications

A soil moisture estimation model is currently being applied for irrigation scheduling. This model was developed by Hanks (1974) and modified by Hubbard and Hanks (1983) and Robinson and Hubbard (1990). The performance of the model under corn, wheat, soyabean, sorghum, and alfalfa crop cover and under different soil types is evaluated by Robinson and Hubbard (1990). They have shown that the model estimates for root zone soil water are satisfactory. The model is based on the following framework:

\[ S = S_0 + P + I - ET - R_o - D_r \]

where \( S \) (mm) is soil water in the root zone, \( S_0 \) (mm) is 24-hours-ago soil water in the root zone, \( P \) (mm) is precipitation, \( I \) (mm) is irrigation, \( ET \) (mm) is actual evapotranspiration, \( R_o \) is runoff, and \( D_r \) is drainage below the root zone. Initial soil water, precipitation, and irrigation (if applied for an irrigated crop) are inputs to the model. Runoff was estimated as any liquid precipitation above 25 mm during a 24-hour period. The role of varying permeability and infiltration rates due to changing soil surfaces was taken into consideration during determination of this runoff threshold value. In this model, drainage is calculated by an equation proposed by Campbell (1985).

The model separately calculates actual evaporation and transpiration, and the summation of the two is \( ET \). A modified version of Penman’s (1948) combination method of potential \( ET \) estimation is used to derive actual \( E \) and \( T \). This modification of the Penman method is conducted by applying a wind function proposed by Kincaid and Heermann (1974). Finally, actual evaporation is a function of potential \( ET \) and the number of days \((d)\) since the last precipitation occurred. This relationship can be expressed as follows:

\[ E = ET_p (1/d)^{0.5} \]
where $ET$, is potential evapotranspiration based on modified Penman method. Actual transpiration is a function of crop and phenology specific crop coefficient ($K_c$), $ET_p$, and a soil water reduction factor ($f$). The soil water reduction factor restricts crop water use when soil moisture content approaches wilting point. Note that this reduction factor is a function of available soil water and water-holding capacity of the soil and changes in response to the ratio of available water to potential available water. Actual transpiration can be expressed as follows:

$$T = (f)(K_c)(ET_p - E)$$

The model was validated and its performance was evaluated for various crops and sites (representing varied soil conditions) in Nebraska (Robinson and Hubbard, 1990). Recent applications show that the model is simulating soil water satisfactorily. As a result, it is currently being used by a number of farmers for irrigation scheduling. The users can access this model through the HPRCC web page and run it for irrigation scheduling. In addition, the soil moisture model simulates water-holding capacity, current water stress, runoff, drainage, phenology, actual and potential evapotranspiration (shown above), sensible heat flux, and net radiation, among others.

The model is therefore applied to McCook, Nebraska, for irrigated and rainfed corn and rainfed grass. Irrigated and rainfed corn represent altered landscape as human settlements continue to expand and rainfed grass represents natural landscape before expansion of agriculture at the turn of the 20th century. This paper presents examples of model applications from two hydrologically strikingly different years, 1988–89 and 1993–94, for these land uses (Figures 2a–c; 3a–c). Note that severe drought and flooding characterize the hydrologic conditions of 1988 and 1993, respectively. Note that the following discussion will primarily be focused on the crop growing period (emergence through harvesting).

Figures 2a, b, and c present estimated soil water in the root zone and energy flux under irrigated and rainfed corn and rainfed grass during 1988–89. Root zone soil water conditions were noticeably different for these three types of land use. Under irrigated conditions, available soil water was at the relatively higher level (> 20 cm) during the initial growth stage of corn plant (Figure 2a). Supply of irrigation water helped to maintain this level. It was quite evident that for all three types of land use, available soil water for plants decreased as the growing season progressed (Figures 2a–c). Obviously, plant extraction and transpiration, soil evaporation, and drainage resulted in this decrease of available soil water. It was found that under irrigated conditions, available soil water never decreased at the same level as it did under rainfed corn. In this case, water was supplied through irrigation to reduce the crop’s exposure to stressful conditions. Thus, the amount of available soil water was relatively higher for irrigated corn compared to two other land uses. Figures 2a and b show that under irrigated corn, available soil water did not fall below 8 cm during its growth period. On the other hand, for rainfed corn, available root zone soil water decreased to nearly 2 cm. This amount is lower than available root zone soil water for rainfed grass (≥7 cm). Soil water depletion for rainfed corn is vigorous compared to rainfed grass. Higher demand of water by corn plants resulted in such depletion.
Figure 2. Energy partitioning during 1988–89 under three different land uses: (a) irrigated corn, (b) rainfed corn, and (c) rainfed grass.
Figure 3. Energy partitioning during 1993–94 under three different land uses: (a) irrigated corn, (b) rainfed corn, and (c) rainfed grass.
Comparison of irrigated and rainfed corn for 1988 shows a similar pattern and magnitude of latent energy (LE) flux up to midway through the corn-growing season (67 days). However, around approximately day 100 after emergence and onward, LE flux reduces to near zero under rainfed corn land use (Figure 2b). On the other hand, for irrigated corn, LE flux reduces to near zero ≈145 days after emergence (Figure 2c). This difference in LE flux has also influenced sensible heat flux (H) during the later half of the corn growth stages. Estimates for these two types of corn growing conditions show that for rainfed corn, energy is predominantly being partitioned as H flux away from the canopy (Figures 2a and b) after ≈ day 73. For irrigated corn, this type of energy partitioning occurs during the crop harvesting stage. For grass, estimated daily LE flux never reaches as high as it does for corn. Figures 2a–c show that occasionally LE flux reaches well above 350 Wm⁻² under corn but ≤250 Wm⁻² for grass. During its growth, H flux from the grass-covered surface shows a pattern generally similar to that from rainfed corn.

Analyses of 1993–94 (a wet year) estimations show that root zone available soil water for all three crops never decreased to the level of 1988–89. For any day, the lowest available soil water for irrigated corn, rainfed corn, and grass was 8, 11, and 12 cm, respectively (Figures 2a–c and 3a–c). Daily LE flux for irrigated and rainfed corn during 1993 did not show a steady increase as the crop grew and then a slow decrease as the crop matured, like 1988 (Figures 2a, b and 3a, b). Instead, the 1993 LE flux maintained a stable rate with regular daily variations. Wet soil conditions, due to frequent rain events, resulted in this type of energy partitioning. Up to nearly day 121, daily H flux for all three crops showed a similar type of variation as the season progressed. During this period, H flux was largely partitioned toward the crop. However, rainfed corn and grass-covered surfaces started to partition most of the energy as H flux away from the canopy surface after day 121. This occurred because of the maturing of these two crops.

Overall, it is clear that LE flux showed more variations during 1988 than during 1993, H flux away from the crop canopy was more common in 1988 than in 1993, and soil water storage was higher at the end of 1993–94 than at the end of 1988–89. Impacts of land use types on soil water and energy partitioning are relatively more evident under dry conditions (1988). Analysis of data shows H flux is higher from grass-covered surfaces compared to rainfed and irrigated corn (Figures 2a–c). Also, rainfed corn partitioned more H after day 97 compared to irrigated corn. As noted previously, under rainfed corn, land use soil water storage is minimal because of the higher amount of extractions by plants. In addition, it is evident that days to reach maturity also influences energy partitioning. Rainfed corn variety (used in this study) and grass require fewer days to reach maturity, compared to irrigated corn. As a result, irrigated corn continued to partition energy as LE for a longer period of time than rainfed corn and grass. It can be concluded from the above discussion that land use plays an important role in energy partitioning.

Final Remarks

We believe application of the soil moisture network’s measured data has significant potential. The Nebraska Climate Assessment and Response Committee (CARC) is currently using soil water data for drought monitoring. They have found that this network is very useful for emergency response and drought mitigation-related activities. Also, with an expanded network, more accurate flood forecasts may be possible. Applications of soil
moisture models and analyses of results show that land use and prevailing weather conditions can significantly alter various components of the energy balance. In other words, this type of modification of energy balance components certainly is able to change the state of boundary layer atmospheric condition. Thus, measured soil water data by this network and the soil model water balance can further be used to determine the role of soil water and land use in modification of boundary layer atmosphere and climate of this region.

Acknowledgments

The authors thank Sebastien O. Korner for his help in preparation of Figure 1.

References

Initial Observations of Seasonal Climate (Temperature) Outlooks

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School of Natural Resource Sciences, University of Nebraska, Lincoln

Abstract

In the late 1980s, the National Climate Program Office recommended that an experimental climate forecast program be established to develop and improve the predictive capabilities of climate forecasts for natural resource management and to enhance the nation's economy. In January 1995, the Climate Prediction Center (CPC) began issuing experimental long-lead seasonal climate outlooks, predictions of climate up to one year in advance, for the contiguous United States on a running 3-month time period. However, skill levels of climate outlooks, both temporally and spatially, need to be assessed to provide decision makers and researchers the degree of confidence to place in the climate outlook products. We analyzed outlooks for the High Plains region using a frequency analysis. The skill of the models used to generate the temperature outlooks, particularly the general circulation model, is highly correlated with teleconnections associated with ENSO events. We found that when outlooks called for above-normal temperatures, short lead times (0.5–5.5 months) during the summer through spring seasons (JAS–MAM) were most accurate. We also found that when outlooks called for below-normal temperatures, long lead times (6.5–12.5 months) during the spring through summer seasons (MAM–ASO) were most accurate. In years in which teleconnections either are not apparent or are not strong (i.e., non-El Niño/non-La Niña years), outlook divisions will often be assigned "CL," suggesting that climatology be used.

Introduction

In the late 1980s the National Climate Program Office recommended that an experimental climate forecast program be established to develop and improve the predictive capabilities of climate forecasts for natural resource management and to enhance the nation's economy (Changnon et al., 1990). In January 1995, the Climate Prediction Center (CPC) began issuing experimental long-lead seasonal climate outlooks, predictions of climate up to a year in advance, for the contiguous United States on a running 3-month time period (van den Dool, 1994).

The seasonal climate outlooks are derived from a combination of two statistical models (the optimal climate normals and canonical correlation analysis models), and one dynamic model (a coupled ocean-atmospheric model). CPC also uses a soil moisture model, a screening multiple linear regression tool, and a global trend signal as additional tools for their outlooks (CPC, 1998).

In the middle of each month, climate outlooks are posted to the CPC web site for each of the 13 subsequent running 3-month seasons. Lead times range from 0.5 months to 12.5 months (Briggs and Wilks, 1996). For example, an outlook produced in mid-January will give a 0.5 month lead time for February–March–April, a 1.5 month lead time outlook for March–April–May, and so on. Thus the outlooks produced in mid-January will extend to
the February–March–April season of the following year for a lead time of 12.5 months. Current season outlook maps (http://www.cpc.ncep.noaa.gov/products/predictions/multi_season/13_seasonal_outlooks/color/page2.gif) show the 0.5-month lead time for precipitation and temperature outlooks (Figure 1). However, CPC also publishes all 13 seasonal outlooks for temperature and precipitation at http://www.cpc.ncep.noaa.gov/products/predictions/multi_season/13_seasonal_outlooks/color/page3.gif (Figure 2) and page4.gif (Figure 3), respectively. These maps are color-coded according to probabilities.

Climate outlook probabilities are divided into three categories: above normal, near normal, and below normal. Each category occurs 33.3% of the time based on the 30-year climate normals (1961–90). The near-normal category stays in the 33.3% range while the above- and below-normal categories are allowed to rise and fall inversely (CPC, 1995). In other words, if the probability of the above-normal category increases to 43.3%, then the below-normal category decreases to 23.3% and the near-normal category remains at 33.3%. The probability anomaly in this case would be a 10% likelihood of above-normal temperatures or precipitation. However, if the CPC feels strongly that an area will be normal, it can assign a higher probability to the normal category at the expense of the above-normal and below-normal categories.

When CPC models cannot produce satisfactory skill for a precipitation or temperature outlook, areas are assigned an equal probability—33.3% above normal, 33.3% near nor-

![Climate Outlook Maps](http://www.cpc.ncep.noaa.gov/products/predictions/multi_season/13_seasonal_outlooks/color/page2.gif)  ![Climate Outlook Maps](http://www.cpc.ncep.noaa.gov/products/predictions/multi_season/13_seasonal_outlooks/color/page3.gif)

**Figure 1. Example of a 0.5-month lead time outlook for precipitation and temperature.**

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Figure 2. Example of a temperature outlook map for 13 seasons representing 0.5- to 12.5-month lead times.

Figure 3. Example of a precipitation outlook map for 13 seasons representing 0.5- to 12.5-month lead times.
normal, and 33.3% below normal—and are then designated as “Climatology (CL)” (Briggs and Wilks, 1996). Since most of the inputs to the models for the outlooks are closely related to ENSO events, the skill of these models reflects this dependence on ENSO events. Areas that have no known teleconnections to ENSO events are likely to be designated CL. In the absence of ENSO events, most of the United States is likely to contain mostly CL outlooks. Because many decision-making processes are determined by climate variation, these outlooks of seasonal climate may potentially aid decision makers in areas such as agriculture (Saulesleja and Olsson, 1997; Meyer, 1994; and Chenault, 1996 and 1998), forestry and fishery management (Baier, 1997), fire management (Hoadley, 1994), drought and water management (Wilhite, 1996 and 2000), human health (Jendritzky and Kalkstein, 1997), and energy use (Changnon et al., 1990). However, skill levels of climate outlooks, both temporally and spatially, need to be assessed to provide decision makers and researchers the degree of confidence to place in the climate outlook products. With confidence, decision makers may tailor their management plans to take advantage of or mitigate the effects of climate variability.

In this chapter, we present preliminary observations of the spatial and temporal accuracy of the long-lead seasonal climate outlooks.

**Materials and Methods**

CPC consolidated the 344 climate divisions in the contiguous United States into 102 aggregated outlook divisions. Spatially, these aggregated outlook divisions are of roughly equal size (Tinker, 1999; Unger, 1999). Our analysis examined only those outlook divisions within the High Plains region (Figure 4).

From CPC we received the following data for each outlook division in the High Plains region: seasonal outlooks, observed temperature, and temperature thresholds for determining terciles. For each 3-month season, we designated the average seasonal temperature in each outlook division as above normal, near normal, or below normal, based on the threshold values supplied by CPC.

1. We analyzed the data using a frequency analysis. Using this technique, we first examined all outlooks collectively. Then, we reexamined the data analyzing only those outlooks that CPC assigned greater than 5% additional weight (i.e., those outlooks in which CPC placed greater confidence). Finally, we examined only those outlooks to which CPC assigned “Climatology.”

**Preliminary Results and Observations**

Since 1997, much of the United States has been under the influence of El Niño/La Niña. The skill of the models used to generate the temperature outlooks, particularly the general circulation model, is highly correlated with teleconnections associated with ENSO events. Therefore, since their inception in January 1995, it is likely that more than half of all seasonal climate outlooks have been derived while taking into account ENSO-related teleconnections. With this in mind, we make the following observations regarding seasonal climate outlooks in the High Plains region:
Figure 4. The 102 outlook divisions aggregated from the 344 climate divisions in the contiguous United States. The outlined area represents those outlook divisions within the High Plains region.

- When the frequency analysis was applied to all seasonal outlooks collectively, we found that above-normal outlooks exhibited particularly good accuracy:
  - in 1997, 1998, and 1999 (the El Niño/La Niña years)
  - over most of the High Plains region (the exception being the central High Plains area of western South Dakota and central Nebraska)
  - for short lead times (0.5–5.5 months)
  - during the summer through spring seasons (JAS, ASO, SON, OND, NDJ, DJF, JFM, FMA, MAM)

- When the frequency analysis was applied to all seasonal outlooks collectively, we found that below-normal outlooks exhibited particularly good accuracy:
  - over the majority of the High Plains region
  - for long lead times (6.5–12.5 months)
  - during the spring to summer seasons (MAM, AMJ, MJJ, JJA, JAS, ASO)

- When the frequency analysis was applied strictly to outlooks assigned greater than 5% additional weight, we found:
  - above-normal outlooks exhibited good accuracy throughout the High Plains region
  - below-normal outlooks exhibited good accuracy in the western High Plains, but poorer accuracy in the eastern High Plains
• When the frequency analysis was applied to all seasonal outlooks collectively, we found that near-normal outlooks were consistently poor

In years in which teleconnections either are not apparent or are not strong (i.e., non-El Niño/non-La Niña years), outlook divisions will often be assigned “CL,” suggesting that climatology be used. This does not necessarily imply that outlooks of “CL” are not useful. However, further research is needed to glean useful information from “CL” outlooks. Below are our observations regarding “CL” outlooks.

• The percent of time “CL” is assigned by CPC tends to be regionally dependent:
  • outlook divisions in the southern and eastern High Plains (i.e., Iowa, eastern Nebraska, and Kansas) tend to have fewer “CL” outlooks (< 50% of the time)
  • “CL” outlooks make up 50–59% of all outlooks for the central High Plains (South Dakota, western Nebraska, and eastern Colorado)
  • outlook divisions in the northern High Plains, Rocky Mountain foothills, and Rocky Mountains (North Dakota, Wyoming, and western Colorado) have “CL” outlooks much of the time (> 60%)

• There is a seasonal cycle in “CL” outlooks, apparently associated with changing seasons:
  • there is a minimum of “CL” outlooks in the summer season (JJA)
  • there is a secondary minimum of “CL” outlooks in the winter season (DJF)
  • there is a maximum of “CL” outlooks in the spring season (MAM)
  • there is a secondary maximum of “CL” outlooks in the fall season (OND)

• In general, the percentage of “CL” outlooks increases with lead time

• When outlook divisions are assigned “CL” temperature outlooks in non-El Niño/ non-La Niña years (1995 and 1996), they tend toward being below normal in the High Plains

• When outlook divisions in the High Plains are assigned “CL” temperature outlooks in El Niño/La Niña years (1998 and 1999), they tend toward being above normal

• When outlook divisions in South Dakota, eastern Nebraska, and Kansas are assigned “CL” temperature outlooks, there is a greater than 50% likelihood that observed temperatures will be below normal

• At short lead times (1.5–3.5 months), there is a tendency for “CL” outlooks to observe below-normal temperatures

• When outlook divisions in the High Plains are assigned “CL” temperature outlooks during spring–early summer seasons (MAM–MJJ), observed temperatures are usually below normal

• When outlook divisions in the High Plains are assigned “CL” temperature outlooks during fall–winter seasons (SON–JFM), observed temperatures are usually above normal

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A Look at Current State, Regional, and Federal Networks
The COOP Network Modernization Initiative

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**Abstract**

An initiative to modernize COOP (Cooperative Observer Program) sites will provide the United States with the spatial density of temperature and precipitation observations necessary to track climate variability at regional and local levels to support monitoring and prediction activities from a few weeks to multi-seasons. The initiative is the result of increased demands for higher density, real-time surface data from weather-sensitive industries as well as private and public weather services. This modernization effort will encompass about 8000 of the 11400 COOP sites. The effort is expected to result in greater efficiencies in maintenance, management, and quality control of COOP data, as well as an increase in the number of applications for data. This chapter discusses various aspects and benefits of the initiative and outlines project milestones.

**Introduction**

This initiative provides the nation with temperature and precipitation observations necessary to quantify climate variability at regional and local levels in support of monitoring and prediction activities from a few weeks to multi-seasons. Implementation of the initiative would ensure accurate surface data from the state-of-the-art Cooperative Observer Program (COOP). Thus the data would be universally available in near real time (i.e., usually within 1 hour of observation time).

This initiative is driven by an exploding demand for higher-density, real-time surface data by weather-sensitive industries and private and public weather services, far in excess of current capabilities. The National Weather Service also requires accurate, non-airport, real-time data to improve its local warnings and forecasts and verification programs. At non-airport locations, the COOP data are the cornerstone for monitoring, documentation, and analysis of regional weather and climate variability, and as such play critical roles in the development and verification of both weather and climate prediction models and techniques.

Current COOP instrumentation and methods for precipitation and temperature measurement are antiquated and will begin to fail by FY2002 and 2004, respectively. Attention will be directed immediately (FY2000–2002) to launching a COOP "rescue" effort to prevent catastrophic failures of critical observing equipment at existing COOP sites and avoid compromising the nation's longest surface weather record. This "rescue" effort is critical to maintaining NOAA's ability to analyze and monitor climate and weather variability as well as to develop, calibrate, and verify climate prediction models. Thus, most (2700) of the existing Fisher & Porter (F&P) precipitation measuring gauges and some (5000) Maximum-Minimum Temperature System (MMTS) display devices must be refurbished immediately, with the intent to eventually replace them with fully automated systems.

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The modernization will be guided by network studies to identify the weather and climate requirements of NOAA, its federal partners (especially the United States Department of Agriculture [USDA]), and its constituents. All interested parties have been closely consulted in the planning and design of the network. Consequently, the studies will need to simultaneously address the number and distribution of sites for different types of observations (including soil moisture and pan evaporation [these observations will be available at 1000 of the 8000 modernized sites]); requirements for accuracy, reliability, and reporting frequency of the observations; and priorities for the modernization sequence of all selected sites. A substantial number of the current 11400 COOP sites are expected to be fully modernized. The current estimate is 8000 COOP locations. The remaining sites will be retained but not fully modernized. Additionally, the initiative will provide real-time access to the 8000 locations. This real-time access to the COOP network data will allow substantially more accurate real-time corrections to biases in the weather radar precipitation estimates. Modernization and real-time access will also allow more efficient network maintenance, management, and quality control.

The benefits from COOP modernization include greater efficiencies in maintenance, management, and quality control of COOP data. In addition, real-time access of data will lead to an enormous number of new applications by both the public and private sectors. For example, real-time calibration of weather radar precipitation estimates will improve. The enhanced ability of NOAA forecasters to monitor developing conditions in critical weather situations should significantly reduce losses from these events. Real-time surface observations will open up broad new opportunities for private sector decision makers to mitigate adverse impacts and realize economic advantages in developing weather and climate scenarios. The latter will be particularly true for rapidly expanding applications in the insurance, reinsurance, and weather risk management industries.

Under NOAA’s Office of the Federal Coordinator, two working groups were established in FY1999 to address COOP modernization. These two groups, made up of several federal agencies, including USDA, Department of the Interior, U.S. Army Corps of Engineers, and Department of Commerce, developed the requirements and cost breakdowns for replacement and modernization of the COOP program. The federal agencies involved in the working groups have concurred that contract support will be required to perform a network density study on the required number of COOP sites to modernize. The contract support will allocate appropriate risk between the government and contractor and will take maximum advantage of the available commercial technology.

Real-time COOP data is the most spatially detailed surface data, providing Weather Forecast Offices with the essential basic observations required for accurate local forecasts and forecast verification. Development of additional components, such as soil moisture and pan evaporation, will provide the nation with a stronger information base for improved monitoring and prediction of drought for critically sensitive regions. COOP data comprise the premier surface climate record in the world and the only surface network providing the nation with accurate snowfall and precipitation measurements, making it of crucial importance to climate monitoring, analysis, modeling, and prediction. (Many private mesonets do not adhere to federal instrument and siting standards, are not spatially comprehensive, do not measure snowfall and snow depth, and have a limited historical record.)
Socioeconomic Benefit—In addition to meeting the original 1890 agriculturally oriented mission to describe the climate of the United States, real-time COOP observations will support a multitude of other critical applications of climate and weather data by industry, government, and individuals. These include mitigation and economic exploitation of climate change and variability, NOAA forecast and warning processes, water management, drought assessment, presidential disaster declaration, crop yield forecasts, energy consumption models, litigation, engineering, power plant and architectural design, recreation, public service, flood zone determination, and financial activities.

Risk Assessment—This initiative will conduct studies on potential future observing sensors and communication equipment. The basic set of measurements will minimally include those for temperature, precipitation, and snow depth.

Impact—Modernization of weather data measurement, collection, and access processes represents an enormous investment and will change the way systems are maintained, managed, and quality-controlled. Consequently, NWS must expand and improve the first-level maintenance training for NWS personnel through hands-on, face-to-face training at the NWS Training Center, and complementary individualized training materials such as computer-based instruction, VHS video, and Internet home page. This effort must be reinforced with regional emphasis on site visits, observer consultation and feedback, and technical training provided by NWS personnel. Network studies with other participating federal agencies will consist of developing, obtaining, and implementing the replacement equipment through a competitive procurement process.

Internet Technology—A COOP web site was opened for public access in late September 1999 (http://www.coop.nws.noaa.gov). The web page, in addition to providing basic programmatic information for all interested parties, will, as part of this initiative, include documentation on standards for instrumentation and exposure, and links to other NWS offices, the National Climatic Data Center, Regional Climate Centers, and state climatological offices. Additionally, the COOP Station Service Accountability (CSSA) system will be revised to ensure that accurate and consistent metadata are collected and made available to users in near-real time via the Internet. Real-time collection and access of the metadata for operational use will be provided through the CSSA and a central web-based server.

Project Milestones:  
FY02: Rescue about 900 COOP F&P gauges and 900 MMTS. Conduct network studies addressing all aspects of system planning, development, and implementation, fully accounting for all public and private constituent requirements.

FY03: Rescue 900 F&P gauges and 2050 MMTS. Begin procurement and deployment of modernized COOP network with new precipitation gauge and temperature systems at approximately 1000 sites per year.

FY03: Begin procurement and deployment of real-time collection and Internet dissemination capability for the COOP network. Continue COOP network modernization at the rate of 1000 per year through FY09.
FY04: Procure and install agriculture-related system components identified in the network studies. Continue COOP network modernization at the rate of 1000 per year through FY09.

FY05: Continue gauge and instrument modernization and complete real-time communications implementation. Complete procurement and installation of agriculture-related system components.

FY06: Continue COOP network modernization at the rate of 1000 per year through FY09. Complete procurement and deployment of real-time collection and Internet dissemination capability for the COOP network.

FY07–09: Complete COOP network modernization.
SNOTEL (SNOwpack TELemetry) and SCAN (Soil Climate Analysis Network)

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Abstract
The Natural Resources Conservation Service (NRCS), National Water and Climate Center (NWCC), operates and manages two unique hydroclimatic data collection systems. For more than 20 years the SNOTEL system has provided critical high elevation climate information from the major water yield areas of the mountainous West. This system plays a key role in providing near real-time precipitation, air temperature, and snowpack information to forecast streamflow volumes. SNOTEL also provides critical information for emergency management agencies to effectively mitigate floods, avalanches, and other life- and property-threatening events associated with extreme weather events.

The NRCS has operated the national Soil Moisture/Soil Temperature (SM/ST) Pilot Project since 1991. This project is nearing completion. The project was conceived because the ability of NRCS and its partners to make sound resource assessments and watershed decisions has been severely limited by the lack of quality historic and real-time soil-climate information. Existing data from other networks are essentially inadequate for most purposes. They tend to be application specific, short-term, incomplete, and limited in area of coverage, and they often include nonstandard data that are difficult to access. SCAN is the next step to implementing a nationwide soil-climate network. When fully funded, it will develop products that increase our customers' ability to make sound resource management decisions. This paper describes both networks: SNOTEL and SCAN.

Meteor Burst Communication
Both SNOTEL and SCAN data collection systems use meteor burst communication techniques to obtain near real-time data from remote sites. The NRCS pioneered the use of this technology in the mid 1970s for use with SNOTEL. Meteor burst communication was chosen for SCAN because of its proven reliability and cost effectiveness.

Meteor burst communication, developed by the military in the 1950s, uses the ionized gas trail from the billions of sand sized-particles (1 gram or larger) that burn up in the 50- to 80-mile-high region of the atmosphere to relay radio signals back to the earth (see Figure 1). VHF radio signals can be bounced off this gas trail and reflected back to the earth. Such signals generate a communications footprint on the earth. Remote sites located in the footprint can transmit data to the master station (Schaefer, 1990). This technique allows communication to take place between a remote site and a master station up to 1200 miles apart. At the master station, the data are checked for completeness. If complete, an acknowledgment message is sent back to the remote site instructing it not to transmit again until its next scheduled time. All three transmissions take place in less than a tenth of a second.
The NRCS owns and operates two master stations near Boise, Idaho, and Ogden, Utah. Only one master station is required to communicate with the remote site network, but two are used to decrease wait times and provide redundancy for the network. These master stations act as central receiving facilities and are linked with the NWCC Central Computer Facility (CCF) by a packet-switched X.25 telephone communication system with Portland, Oregon. The NRCS currently leases a third master station, located in Tipton, Missouri, to extend coverage to the central and eastern United States. Data received from the master stations are transferred to the CCF continuously.

Data Collection Networks

SNOTEL: In 1978 the SNOTEL system began sending high elevation climate information in near real-time via meteor burst telemetry. SNOTEL was the first and remains the largest user of meteor burst communication technology in the world (Schaefer, 1990). Currently, this network operates more than 650 remote sites in the western United States and Alaska. Table 1 describes the typical sensor array that is commonly available at most remote sites.

The SNOTEL system will accommodate a variety of other sensors, including wind speed, wind direction, relative humidity, solar radiation, water level, soil moisture, and soil temperature.

Table 1. SNOTEL site configuration.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow water content</td>
<td>Snow pillow device and pressure transducer</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Standard 12-inch orifice, alter shielded, all-season storage</td>
</tr>
<tr>
<td></td>
<td>gauge</td>
</tr>
<tr>
<td>Snow depth</td>
<td>Sonic sensor</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Shielded thermistor</td>
</tr>
</tbody>
</table>
Figure 2. Mt. Rose Ski Area SNOTEL site, Nevada.

Most SNOTEL stations provide multiple measurements per day and can provide hourly data on request (Schaefer and Werner, 1996). Approximately 30% of the 650-station network provides hourly data. All remote sites are operated in an unattended mode and rely on solar panels and batteries for electrical power. Figure 2 shows a typical SNOTEL remote station.

System reliability is generally 99%, as measured at midnight when every site is expected to report. The data from the remote sites go through an initial electronic screening before being placed into the database. Once in the NRCS database, numerous automatic reports are generated and the data are made available to the public via the World Wide Web and other means. SNOTEL data are electronically transmitted hourly to the National Weather Service and to other federal and state entities for their use.

The primary uses of the SNOTEL system are for making snowpack assessments and water supply forecasting. SNOTEL also plays a major role in mitigating drought and flood impacts. This system is unique and is the only system that provides high elevation climate information in near real-time.

SCAN: SCAN uses much of the technology that was developed for SNOTEL. SCAN uses the same meteor burst communication technology as SNOTEL, on a nationwide basis. NRCS leases a third master station, located in Tipton, Missouri, to provide coverage for the central and eastern sections of the United States. The concept of SCAN was developed
through collaboration between the Soil Survey and Resources Inventory divisions of the NRCS. The Soil Moisture/Soil Temperature (SM/ST) pilot project was started in 1991 to:

1. Develop the technical expertise in monitoring the soil-climate interface
2. Demonstrate the technical feasibility for a nationwide network

The SM/ST pilot project operates 21 stations in 19 states (NRCS Soil-Climate Team, 1995). This is the final year of the pilot project, but the mission continues in SCAN (Cooper et al., 1992). Although SCAN is not currently funded by the agency, cooperators have assisted in beginning the proposed network. Presently the growing SCAN network consists of approximately 40 stations in 25 states, including the original 21 pilot project sites and some SNOTEL sites with soil moisture sensors. Figure 3 shows the locations of current SCAN sites.

![SCAN site locations](image)

**Figure 3. SCAN site locations.**

The SCAN network is configured to report hourly data. SCAN stations use a separate data logger and meteor burst transceiver for greater flexibility in data acquisition. Table 2 describes a typical SCAN station configuration.

Figure 4 shows a typical SCAN site with a full complement of sensors, including a snow pillow and snow depth sensor.

Data loggers enable the use of a variety of sensors at each site. The initial system combined the meteor burst communication instrumentation and sensor polling instrumentation into one unit. The older type device was less flexible in station configuration, but still
Table 2. SCAN site configuration.

<table>
<thead>
<tr>
<th>Parameter measured</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>Storage-type gauge</td>
</tr>
<tr>
<td>Air temperature</td>
<td>Shielded thermistor</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>Thin film capacitance-type sensor</td>
</tr>
<tr>
<td>Wind speed and direction</td>
<td>Propeller-type anemometer</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>Pyranometer</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>Silicon capacitive pressure sensor</td>
</tr>
<tr>
<td>Snow water content</td>
<td>Snow pillow device and a pressure transducer (at selected sites)</td>
</tr>
<tr>
<td>Snow depth</td>
<td>Sonic sensor (at selected sites)</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>Frequency shift dielectric constant measuring device; measurements are at 2&quot;, 4&quot;, 8&quot;, 20&quot;, and 40&quot; where possible</td>
</tr>
<tr>
<td>Soil temperature</td>
<td>Thermistor; measurements are at 2&quot;, 4&quot;, 8&quot;, 20&quot;, and 40&quot; where possible</td>
</tr>
</tbody>
</table>

Figure 4. Mahantango Creek SCAN Site, Klingerstone, Pennsylvania.
allowed for connection of a variety of analog and pulse counter sensors. The new system not only allows the use of most analog, digital, pulse, and SDI12 sensors, but also the conversion of sensor output directly to engineering units at the station.

Data Management
Data management is performed in two stages. The computer automatically validates the incoming value against limits and flags any that fall outside preset windows. Statistical assistants examine any flagged values to determine their accuracy and make corrections. All parameters are graphed and comparisons are made between sensors to verify that the data are within an acceptable range. Based on the findings from this quality control process, maintenance visits are conducted to correct deficiencies. Presently, the SNOTEL system undergoes more extensive quality control screening than does SCAN, which is the result of increased staffing for SNOTEL.

Data Access and Use
SNOTEL and SCAN data are both available via the web. Numerous automated analysis products have been produced using the data provided by SNOTEL. New products are continuously being developed to support user demands. The NWCC home page is http://www.wcc.nrcs.usda.gov.

Beginning in May 1998, SCAN data were placed on the NWCC home page. The web site contains the current and historic data for each site. In addition to the data, each site contains all of the soil pedon information, a site picture, and a “hot link” to the National Soil Survey Center Laboratory database, which contains all of the site characterization (chemical, physical, and mineralogical) information. Data from other Soil Moisture Team projects are also available through this web site. Interest has grown dramatically since the data were made available on the Internet. Figure 5 shows the demand for this type of data as awareness of its existence grows.

The uses for data from these two unique sources are extremely varied. Traditionally, SNOTEL data have been used to produce snowpack analysis and streamflow forecasts at approximately 1000 points in the West (Jones and Shafer, 1992). Because of the period of record that now exists for SNOTEL, other uses can now be found for this data set. Two examples of new uses of SNOTEL information are PRISM (Daly and Johnson, 1999) and improved spatially distributed snowmelt modeling (Garen and Marks, 1996).

The use of the SCAN data is equally varied. The data are being used not only for traditional agricultural purposes such as evapotranspiration calculation and drought assessment, but also applications ranging from pipeline development to cold-season nitrogen-fixing bacteria population prediction. Additional uses of both networks include:

- Monitoring drought development and triggering plans and policies for mitigation
- Soil classification
- Engineering applications
- Input to global circulation models
Figure 5. FTP downloads.

- Development of new soil moisture accounting and risk assessments
- Monitoring and prediction of changes in crop, range, and woodland productivity in relation to soil moisture-temperature changes
- Prediction of regional shifts in irrigation water requirements that may affect reservoir construction and ground water levels
- Prediction of shifts in wetlands
- Prediction of changes in runoff that affect flooding and flood control structures
- Verification and groundtruth satellite and soil moisture model information
- Prediction of the long-term sustainability of cropping systems, and watershed health

Benefits

The general benefits of both systems include real-time monitoring, cost efficiency, low maintenance requirements, and the capability of monitoring additional parameters such as water depth, water quality, and soil redox potential.

Summary

SNOTEL and SCAN have proven technology with which to meet the ever-increasing demands for soil climate information. Additional resources are needed for SNOTEL to adequately cover the snow-producing areas. It is estimated that an additional 800 sites are required to meet the growing demands for snowpack and water resource information.
SCAN is currently an unfunded budget initiative. If SCAN were to be fully funded, it is anticipated that 1000 additional data collection stations would be installed. These new stations will focus on the agricultural areas of the United States. In addition to these new stations, the budget initiative calls for the incorporation of existing networks, through partnerships with NRCS, to add an additional 1000 soil-climate stations for a total network of 2000.

References


A Climate Reference Network for the United States

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Abstract

Although the United States is a leader in climate research, the nation does not have an observing network that can ensure long-term climate records free of time-dependent biases. Such records are essential for the study of climate change and variations. A National Research Council (NRC) study on the adequacy of climate observing systems recommended actions for federal agencies and the scientific community to take to maintain and enhance observational programs. The National Oceanic and Atmospheric Administration (NOAA), in response to NRC concerns, is developing the U.S. Climate Reference Network (CRN), a network of about 250 station pairs. The goal of the CRN is to provide future long-term homogenous observations for detecting present and future climate change. It is part of a multiyear NOAA climate initiative to modernize the COOP network and create a network meeting Global Climate Observing System (GCOS) standards for long-term climate monitoring.

The Ten Climate Monitoring Principles identified by the NRC in their study are being used as guidelines in the network’s development. The development of the CRN has been divided into ten tasks, centered on determining equipment specifications and requirements, installation and maintenance procedures and schedules, backup instrumentation, and metadata needs; developing calibration and validation methodology, physical transfer models, and a quality control and management system; identifying training needs; defining criteria for station selection and standards for siting instrumentation; and coordinating use of CRN data among various organizations. This chapter discusses the work involved in the ten tasks.

Introduction

One of the principal conclusions of the 1997 Conference on the World Climate Research Programme was that the global capacity to observe the earth’s climate system is inadequate and deteriorating worldwide and “without action to reverse this decline and develop the Global Climate Observing System, the ability to characterize climate change and variations over the next 25 years will be even less than during the past quarter century” (National Research Council [NRC], 1999). In spite of the United States being a leader in climate research, we do not have, in fact, an observing network capable of ensuring long-term climate records free of time-dependent biases. Even small biases can alter the interpretation of decadal climate variability and change.
The NRC study further concluded that federal agencies and the scientific community at large should take action to:

- stabilize the existing observational capability;
- identify critical variables that are inadequately measured;
- build climate observing requirements into the operational programs as a high priority;
- revamp existing climate programs and some climate-critical parts of operational observing programs; and
- establish a funded activity for the development, implementation, and operation of climate-specific observational programs.

These recommended actions came as a result of a question asked by the chair of this study: “Are we making the measurements, collecting the data, and making it available in a way that scientists of both today and tomorrow will be able to effectively increase our understanding of natural and human-induced climate change?” (NRC, 1999, p. x).

Overall, the climate community is at a crossroads. On the one hand, we have done the best we can do to document regional, national, and global climate change. On the other hand, to ensure credibility of future climate change assessments, it is necessary for the scientific community to acknowledge that a crisis exists in the quality of our long-term observing systems—a crisis to which it must respond.

The National Oceanic and Atmospheric Administration’s (NOAA) response to the NRC concerns is the U.S. Climate Reference Network (CRN), a network of about 250 station pairs now being developed. The primary goal of its implementation is to provide future long-term homogenous observations for the detection and attribution of present and future climate change. Data from the CRN will be used in near-real time climate monitoring activities and/or placing current climate anomalies into historical perspective. The CRN will also provide the nation with a national reference network that meets the requirements of the Global Climate Observing System (GCOS). Implementation of the CRN is contingent on the availability of federal funding.

**The Ten Climate Monitoring Principles**

The NRC (1999) report identified ten principles that should be applied to climate monitoring systems. These principles are guiding the development of the CRN.

1. **Management of Network Change.** Assess how and the extent to which a proposed change in a climate observing network could influence the existing and future climatology obtainable from the system, particularly with respect to climate variability and change.

2. **Parallel Testing.** Make overlapping measurements to derive transfer functions for converting between climatic data taken before and after a change in an existing observing system, or taken from two parallel systems. The period of overlapping measurements should be sufficiently long to observe the behavior of the two systems over the full range
of variation of the climate variable observed. The preferred \textit{minimum} period of overlap is two consecutive years.

3. \textbf{Metadata}. Metadata are crucial. Fully document each observing system and its operating procedures. This is particularly important immediately before and following any change.

4. \textbf{Data Quality and Continuity}. Assess data quality and homogeneity as a part of routine operating procedures. This assessment should focus on the requirements for measuring climate variability and change, including routine evaluation of the long-term, high-resolution data capable of revealing and documenting important extreme weather events.

5. \textbf{Integrated Environmental Assessment}. Anticipate the use of data in the development of environmental assessments, particularly those pertaining to climate variability and change, as part of a climate observing system's strategic plan.

6. \textbf{Historical Significance}. Maintain operation of observing systems that have provided homogeneous data sets over a period of many decades to a century or more. A list of protected sites within each major observing system should be developed, based on their prioritized contribution to documenting the long-term climate record.

7. \textbf{Complementary Data}. Give the highest priority in the design and implementation of new sites or instrumentation within an observing system to data-poor regions, poorly observed variables, regions sensitive to change, and key measurements with inadequate temporal resolution.

8. \textbf{Climate Requirements}. Give network designers, operators, and instrument engineers climate monitoring requirements at the outset of network design. Instruments must have adequate accuracy with biases sufficiently small to resolve climate variations and changes of primary interest. Modeling and theoretical studies must identify spatial and temporal resolution requirements.

9. \textbf{Continuity of Purpose}. Maintain a stable, long-term commitment to these observations, and develop a clear transition plan from serving research needs to serving operational purposes.

10. \textbf{Data and Metadata Access}. Develop data management systems that facilitate access, use, and interpretation of data and data products by users. Freedom of access, low-cost mechanisms that facilitate use, and quality control should be an integral part of data management. International cooperation is critical for successful data management.

\textbf{Methodology—A Coordinated Approach}

A development team comprising members from several federal and state organizations has been created to establish the CRN. Under the auspices of the Office of the Federal Coordinator for Meteorological Services (OFCM), the interdepartmental Joint Action Group (JAG) is led by the National Climatic Data Center (NCDC) and includes active partici-
pants from the National Weather Service (NWS), the Department of Agriculture (USDA),
the National Oceanic and Atmospheric Administration’s (NOAA) Regional Climate Cen-
ters, several state climatologists, and universities.

The work to develop the CRN has been divided into ten tasks:

1. determine the specifications and requirements for the meteorological sensors, data
   loggers, and communications system;
2. develop equipment calibration and validation methodology;
3. determine equipment installation and maintenance procedures and schedule;
4. determine alternate permanent backup instrumentation at each CRN site;
5. identify training needs, schedule, and frequency for observers and maintenance per-
   sonnel;
6. define criteria for selecting stations and standards for siting the instrumentation at
each station;
7. develop physical transfer models to relate data from the new automated instrumen-
tation to the conventional (historical) instrumentation, and determine data adjustment
   methodologies for the historical data;
8. determine metadata needs (historical as well as new metadata, such as digital photos
   and GIS information) and create a mechanism for updating the metadata and ensur-
ing their quality;
9. develop a data quality control and management system to accommodate the CRN
data; and
10. coordinate the use of CRN data among the various organizations, including how it
will be related to the existing CLIMAT network (international network of monthly
reporting stations).

Specifications and requirements documents have been prepared for each of these tasks. Procurement mechanisms and contractors are being identified for each task.

Instrumentation and Variables to be Measured

Several climate system variables were identified by the NRC (1999) as relevant to the
detection, attribution, and direct societal impacts of climate change. The surface atmo-
spheric variables include air temperature, humidity, wind, radiative (skin) temperature,
sea-level pressure, precipitation, snow cover extent, snowfall, snow water equivalent, sea
ice, fluxes of sensible and latent heat, fluxes of atmospheric trace gases and particulate
material, incident solar radiation and downward longwave radiation, albedo, streamflow
and reservoir volume, ground water, and vegetative cover.

The NRC report assigned the highest overall ranks to the traditionally measured vari-
ables temperature and precipitation. Therefore, in response to the NRC ranking, each
CRN station will measure temperature and precipitation. In addition, wind speed at ther-
ometer height and solar radiation will be measured to establish rigorous transfer func-
tions relating the CRN measurements to historical temperature data recorded at nearby
stations in other networks that have long-term records. These transfer functions will be
based partially on studies conducted by Lin and Hubbard (1999) and Guttmann and Baker
(1996). Soil moisture and soil temperature will be measured using sensors provided by

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the USDA. Hourly observations of these variables will be transmitted in near-real time and summary-of-day statistics will be computed operationally at NCDC. GOES satellite and meteor burst are being evaluated as possible methods of communication.

**Air Temperature**

Air temperature will be measured using aspirated thermometers at a height of 1.5 m. Each sensor will be located at the end of an arm extending from a 3 m (10 ft) mast. Thermometers housed in unaspirated shields in calm air and a solar flux of 1000 Wm⁻² can experience a warm bias of 2–3°C. Each station will have two aspirated thermometers. One thermometer will serve as a backup for the other. In practice, if the two thermometers systematically differ by more than 0.2°C, remedial action will be taken. The problem may be a sensor, an aspirator motor, airflow blockage, or some other cause. Solving the problem will require a technician to travel to the site to perform an independent measurement of temperature at the same height as the station sensors. The results of a few hours comparison under appropriate conditions usually will be sufficient to indicate the source of the problem and what to do about it. Spare calibrated sensors and aspirator motors must be part of the equipment brought to the station.

In the first implementation of about 6 stations, at least 3 aspirated temperature sensors will be used. The purpose is to show whether it is possible to isolate the specific temperature sensor that is defective using the 0.2°C criterion. A tradeoff may occur between the cost of adding a third thermometer and the likelihood of sensor degradation.

Table 1 shows that the range in temperature expected in the continental United States, including Alaska, is -60°C to +60°C. This range includes observations at Fairbanks, Alaska, and Death Valley, California. In the laboratory calibration using an environmental chamber, the range of calibration temperatures will vary according to the station location where the sensor will be placed. For example, a temperature sensor to be used in south central Florida need be calibrated in a laboratory only from 0°C to 40°C. For the far northern United States, from the Rocky Mountains eastward to Maine, where continental climate prevails, the range may vary from -60°C to 35°C. Deciding in advance where a particular sensor is to be located in the network can reduce calibration time and costs. The actual laboratory calibration procedures are being developed.

Field calibration using laboratory-calibrated sensors will be performed in response to systematic differences between temperature observations (discussed earlier) as well as periodic comparisons. The latter will be performed at 3-month intervals during the 9-month Field Evaluation Phase. After a station is commissioned, the field comparison may be performed every 6 months or, perhaps, annually, depending on results from the Field Evaluation Phase.

**Precipitation**

Because of the need to have an accurate measurement of precipitation rate, a weighing-bucket gauge, as opposed to a tipping-bucket gauge, will be used to measure precipitation. In suitably high rainfall rates, the undercatch due to rain falling while the bucket is tipping can be substantial (McKee et al., 1995 and 1996). For example, with a rainfall
Table 1. Instrument specifications for the four primary variables to be measured by the Climate Reference Network.

<table>
<thead>
<tr>
<th></th>
<th>Temperature</th>
<th>Precipitation</th>
<th>Wind speed</th>
<th>Solar radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling interval</td>
<td>2 seconds</td>
<td>1 minute</td>
<td>2 seconds</td>
<td>2 seconds</td>
</tr>
<tr>
<td>Reporting frequency</td>
<td>hourly</td>
<td>hourly</td>
<td>hourly</td>
<td>hourly</td>
</tr>
<tr>
<td>Range</td>
<td>-60°C→+ 60°C</td>
<td>capacity: 600 mm (24 in)</td>
<td>&lt; 0.5–50 m/s</td>
<td>0–1500 W/m²</td>
</tr>
<tr>
<td></td>
<td>maximum rate: 30 mm/min (1.25 in/min)</td>
<td>0.1 m/s</td>
<td>1 W/m²</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1°C</td>
<td>0.2 mm (0.01 in)</td>
<td>Accuracy: +/- 0.2 mm ( +/- 0.01 in) or +/- 2% of rdg, w.e.i.g.</td>
<td>+/-5% of daily total</td>
</tr>
<tr>
<td>Accuracy (inaccuracy)</td>
<td>+/- 0.3°C</td>
<td>+/- 0.2 mm ( +/- 0.01 in)</td>
<td>or +/- 2% of rdg, w.e.i.g.</td>
<td>threshold: &lt; 0.5 m/s</td>
</tr>
<tr>
<td></td>
<td>-50°C→+50°C</td>
<td>+/- 2% of rdg, w.e.i.g.</td>
<td>or +/- 0.2 m/s</td>
<td>dist cons: &lt; 2.5 m</td>
</tr>
</tbody>
</table>

rate of 200 mm h⁻¹, the undercatch can be 10–15%. The observed rainfall can be corrected to some degree, but it is a difficult task. In addition, if the data sampling rate is, for example, 1 minute (as in Table 1), a discretization error occurs because the time-of-tip of the bucket is unknown. The error is dependent on the number of tips per sample interval. Neither problem occurs using a weighing-bucket gauge. The tradeoff between the two methods is cost. A weighing-bucket gauge is easily 3 times more expensive than a tipping-bucket gauge because of the intricacy of the weighing mechanism.

The problem of undercatching precipitation gauges (Grosisman and Legates, 1994), resulting from wind-induced turbulence at the gauge orifice and wetting losses on the internal walls of the gauge, can seriously affect the utility of precipitation data for climate change studies. Accurate snowfall measurement can be particularly problematic. Wind speed is one of two main deterrents to accurate automatic measurement of water equivalent snowfall. The higher the wind speed, the greater the undercatch. There are a number of ways to reduce the “wind effect,” including the use of one or more wind shields (WMO, 1996). A field experiment was carried out this past winter at the National Center for Atmospheric Research (NCAR) and funded by CRN to investigate the use of 3 concentric wind shields or fences to significantly reduce snow undercatch. The 3-fence combination is based on the WMO Double Fence Intercomparison Reference (DFIR). The CRN ver-
sion is smaller in diameter and has an alter shield as the innermost fence. Gauge rainfall measurements are similarly affected by the speed of the wind, but the undercatch is typically much smaller. The second main source of error is the build-up of wet snow on the orifice. To reduce this error, the NCAR group investigated methods to efficiently heat the orifice. Other gauge experiments were also conducted.

**Solar Radiation**

Because solar radiation is a secondary variable, a modestly priced silicon photo diode pyranometer (LI COR 200) was selected. Experience has shown the LI COR to be a reliable, robust solar radiation sensor requiring quarterly to semiannual cleaning and annual recalibration. This sensor seems to be particularly susceptible to lightning so that it will be mounted on an arm extending southward from the tower at a height of about 2 m.

**Wind Speed**

Wind speed will be measured with a cup anemometer that generates a square-wave or pulse frequency proportional to wind speed. The anemometer will be mounted at the end of an arm extending outward from the tower at a height of 1.5 m in the direction that minimizes tower interference due to the wind based on climatology. The main cause of degraded wind speed is bearing wear. A comparison to a standard anemometer will be made during each site visit.

**Station Selection**

The CRN is being developed for climate change detection and operational climate monitoring. The stations should be located where they will most likely be able to detect, monitor, and quantify climate variations, where they have a strong likelihood of surviving (i.e., remaining in place for a long period of time), and have nearby at least one station with high-quality long-term records. The quality of the meteorological variables being measured by the CRN is influenced by several factors, one of which is the site representativity and therefore measurement representativity.

Several approaches are being followed in the overall network design. (1) It has long been known that regional climate changes may sometimes be quite diverse (e.g., Lamb, 1977; IPCC, 1990). Climate change projections using global climate models suggest there will be regional differences in the pattern and rate of climate change, although the models have low reliability at the regional spatial scale (IPCC, 1990). Past historical analyses and model projections will guide the placement of CRN stations in climate-change-sensitive regions. (2) NCDC has identified those Cooperative Network stations with at least 80 years of highly reliable and homogeneous data and compiled them into the 1221-station U.S. Historical Climatology Network (US HCN) (Easterling et al., 1996). The US HCN data, and analyses of other data sets (e.g., Guttman et al., 1993), will provide guidance on the development of coherent climate regions and help to assess the optimal number of stations required to represent century-scale climate variability on various spatial scales.

The station selection process will focus on which locations best represent climate-change-sensitive areas and should ensure that, when the CRN network is fully deployed, all
climate regions are covered. Since the CRN data also will be used for operational climate monitoring, complete daily data will be needed in near real-time.

**Deploy CRN Stations at New or Existing Locations?**

The deployment of the CRN stations must strike a balance between locations that are suitable for detecting climate change and locations that have a record that can be used to show if climate change has, or hasn’t, occurred. The CRN initiative promised to put current climate anomalies and climate change into a century-scale perspective. This requires that:

1. If CRN stations are co-located with existing stations that have a long historical record, then that historical data must be of high quality or the inhomogeneities must be corrected with a high degree of confidence.
2. If CRN stations are co-located with existing stations that have a short historical record, or located at sites that have no historical data, nearby high-quality stations must be used to estimate the “historical record” at the CRN station.

Thus to accomplish (1) and (2) it is imperative that a period of overlap of observations, at least 2 years, be made between the CRN station and the surrounding high-quality stations. The longer the period of comparison, the greater the confidence in the modeled historical record at the CRN station.

**Network Considerations**

The NRC (1999) report noted that many federal agencies have observing systems that monitor weather or climate for specialized (mostly nonclimate change) purposes. Examples include the National Science Foundation’s (NSF) Long-Term Ecological Research (LTER) network, the USDA’s Soil Climate and Analysis Network (SCAN) and snowpack telemetry (SNOWTEL) networks, the NOAA Global Positioning Satellite-Integrated Precipitable Water (GPC-IPW) network, and the NWS upper-air, Automated Surface Observing System (ASOS) and Cooperative (COOP) Station networks. Of these, the COOP network is best suited for climate monitoring purposes because many stations have records extending back into the 19th century. However, it suffers from many problems, including inadequate instrumentation, antiquated data handling systems, and historical data inhomogeneities due to changes in instrumentation, location, and observation practices (NRC, 1999). The following hierarchy will be used in the selection of CRN deployment sites and neighbors:

**First Choice:** The US Historical Climatology Network (US HCN) was created with many of the CRN selection criteria in mind. It is therefore the logical choice as the pool from which CRN deployment sites or nearby high-quality stations are selected. However, some parts of the country are poorly represented even in the US HCN network. Consequently, we will need to consider stations in other networks to fill in the gaps.

**Second Choice:** The US HCN stations were selected from the larger Cooperative (COOP) station network pool, and replacement HCN stations would also be selected from the COOP pool. Some currently non-HCN COOP stations may need to be chosen to fill in the gaps.
**Third Choice:** Other federal (and maybe state) agencies might have networks with stations that could serve as effective CRN deployment sites or nearby high-quality stations. We don’t want to exclude them as potential candidates, but if any are chosen they will have to pass our stringent selection criteria (as outlined below), and agreements with the agencies will need to be signed that allow us access to the sites, real-time collection of current and future data, and access to the historical data and metadata.

Accurate and complete metadata are needed for the evaluation process. The metadata for existing stations should be provided by the NCDC and the NWS from their respective (historical [NCDC] and operational [NWS]) station history files, and by other agencies if stations from their networks are used. Knowledge about existing stations obtained by dealing with them on a person-to-person basis should be provided by the NWS DAPMs, Regional Climate Centers (RCCs), state climatologists, and appropriate personnel from other agencies.

Once a location has been identified as a potential CRN site, a qualified climatologist should visit and document the location. Their evaluation should be conducted with a view toward both the present and future suitability of the site for long-term monitoring of climate change.

**Station Selection Criteria**

The following are the criteria to be used in identifying stations or locations as CRN candidate sites:

- Location should be sensitive to climate change.
- Station stability/permanence (want to minimize the chance that the station will close as result of the observer selling the land or other reasons). Stations located on government (federal, state, local) or college land therefore have a higher stability factor. This criterion includes the need for CRN deployment and maintenance personnel to have permanent access to the land where the instruments are sited.
- Station represents the climate of the region (not influenced by unique mesoscale environments or microscale environments such as buildings, trees, or additional anthropogenic factors).
- The historical data record for a co-located station, or the reconstructed record for the CRN site, spans at least 80 years.
- Observed and historical variables must include daily maximum and minimum temperature and precipitation amount.
- The historical data record has a high data quality (minimum inhomogeneities: few changes in location of station or instruments, type of instruments, observation time, observing practices, etc.); able to adjust the data for inhomogeneities with a high degree of confidence.
- Regional climate/spatial representativeness (stations should be selected in a relatively homogeneous manner geographically while ensuring that all major climate regions are represented).
- At least one station in each of the 50 states and as many territories as possible.
• Other geographical considerations (crop regions, river basins, other geopolitical regions, etc.)

Quality of a Measurement
Several factors have an influence on the "quality of a measurement" and the CRN is addressing these factors through steering committees. The three factors that the CRN deems most critical to ensure high quality measurements are as follows:

1. The intrinsic characteristics of the sensors. These include the performance specifications of each sensor. Each manufacturer supplies these specifications, which include range, accuracy, error, and time of response. The CRN steering committee on instruments/system requirements has defined the intrinsic characteristics required to meet the needs of a national climate reference network.

2. The operational maintenance needs that are required to maintain the system over a wide variety of climate regimes. These operations necessitate the replacement of faulty sensors, bench calibration of the sensors traceable to a standard, and annual audits with traveling standards. This preventative maintenance is the best guarantee that the system will be close to the nominal performance and allow the disseminated measurements to be close to the intrinsic performance of each sensor. The CRN committee on equipment calibration and qualification and the CRN committee on equipment installation and maintenance have developed guidelines for this aspect of the CRN.

3. Site representativeness and therefore the measurement representativeness, probably the most-neglected and least-quantified factor for quality measurements.

Station Siting Standards
The physical criteria for siting the CRN stations include:

Location: The goal is to ensure that a high percentage of the sites are in rural areas to avoid anthropogenic factors present in urban and suburban areas.

Representativeness: The physical characteristics of a site, including soil properties, should be uniform in all directions and representative of as large an area as possible. Sites should be located away from irrigated areas, lakes, and other discontinuities in surface vegetation to minimize nonrepresentativeness.

Topography: The land surface should be as flat as possible and there should be a minimum of obstructions that impede the ventilation of the site. The WMO standard is no obstructions within 300 m (WMO, 1996). A rule of thumb based on nonporous shelterbelt experiments suggests that the distance between the anemometer and an obstruction to the wind should be at least 20 times the height of the obstruction.

Accessibility: Each site should be accessible in all weather conditions.

Vegetation: Selected sites should have a uniform low-cover vegetation. Sites that have short grass are preferred.
These are the general criteria. It is quite probable that many sites will be less than ideal. To that end, the CRN will use a classification scheme that is defined for each variable to document the representativity of each site. This scheme was first proposed by Leroy (1998) and is now being used by Meteo France to classify their network of approximately 550 stations. The classification ranges from 1 to 5 for each variable. By convention, a class 1 site will follow the WMO (where applicable)/CRN recommendations. A class 5 site for a particular variable would indicate that it is an inappropriate environment. Further research will be needed to define the error associated with some of the variable classes.

**Metadata**

High-quality data records are central to accomplishing the climate change detection and climate monitoring goals of the CRN, and detailed metadata are crucial to establishing and interpreting a high-quality data record (Robbins et al., 1999; Viront-Lazar et al., 1999). Each component of the observing system and its operating procedures must be fully documented. This is particularly important when changes to the station occur or are contemplated. Historically, metadata has included such variables as latitude, longitude, and elevation of the station and type of instruments and their exposure and height above ground.

The CRN will use modern technology to acquire, store, and present a richer body of metadata. The expanded metadata information will include digital images, instrument specifications, calibration and maintenance records, sampling and validation procedures, and algorithms used to process and quality control the climate data.

**System Requirements**

Experience has proved that system requirements evolve. The COOP station network illustrates the changing nature of networks. The longevity of the station installations, some spanning more than 100 years, has resulted in numerous changes in station location, elevation, sensor type, shelters, site characteristics, observers, observing practices, time of observation, and other documented and undocumented factors. In addition, the network continually evolves and varies, by station, within the network. It was designed primarily as a climate documentation network, and the primary data delivery method was, and continues to be, mailing of monthly forms to a central data collection facility. Originally these data were archived as printed material and were eventually transferred to digital media. A subset of the stations was selected to report observations on a daily schedule to accommodate the needs of operational forecasting, forecast models, and forecast verification. The concept of climate monitoring evolved as well, and the need for near real-time observations has arisen to satisfy the requirements for up-to-date information. The current COOP metadata system does not fully accommodate the dynamic nature of these changes in a comprehensive and timely manner.

CRN metadata system requirements are being developed to build on past experiences with the intent to fully document current system characteristics and practices. The metadata system should also be capable of documenting changes in the physical, conceptual, and administrative characteristics of the system.
Although it is difficult to plan for the unknown, and adding a completely new type of information could require additional tables or screens, a key goal in designing the metadata system is to accommodate changing types of information requirements without changes to the database structure or user interface.

Different numbers and models of instruments, or altogether new instrument types, may be used. Additional meteorological elements may be observed and reported. Sampling and averaging procedures may be modified. To meet requirements for various data transmission systems and to facilitate integration of CRN observations with various data products, additional Network Station Identifiers (COOP ID, WMO ID, UCAN ID, etc.) may need to be assigned to a station. With thoughtful attention to database and interface design, such changes can be accommodated without system modification.

Metadata are dynamic. Instruments, ground cover, station location, personnel, observation practices, processing algorithms, data formats—in short, virtually all aspects of metadata—change over time, and the temporal component is critical to interpreting the data that the metadata describes. To effectively model this changing environment, the system must track change history for all data items over time, with the previous versions or values and their effective change dates available for retrieval.

The CRN metadata database will initially be implemented using the Oracle relational database engine, and will reside at the NCDC. Oracle is a de facto industry standard for high-performance relational database systems, and it provides a variety of means to enforce business rules at the database level, thereby ensuring logical data integrity independent of application-level constraints and checks. The logical data structure is independent of a specific implementation platform, however, and the CRN will evaluate new data representation and management technologies as they emerge.

The system will use a World Wide Web HTML forms-based user interface. A web-based interface will simplify software distribution and support issues, and should shorten the learning curve. To simplify visualization and selection of stations, a map-based geographic query interface is eventually planned to supplement the traditional web-based text approach. The underlying database structure will be independent of the interface, however, so that the user interface can evolve to take advantage of new technologies and techniques as they develop with little or no impact on the database.

Updates and maintenance will be done initially by data management. Eventually the system will provide an interface to permit field personnel to submit updates, which will then be reviewed and accepted or rejected by data management.

Training is difficult to provide for a distributed user base. The interface should require little or no training for a computer-literate user with basic subject matter knowledge. Online documentation will be designed to document system operations and rules as well as data element semantics.

To ensure metadata consistency, the system implementation must be governed by rigorously defined and documented procedures for metadata ingest, quality control and validation checks, and value update.
Metadata Subject Areas

The CRN metadata requirements are grouped into interrelated subject areas. These subject areas are the basis for designing the database and application subsystems.

Station Identification, Location, and Operation

A great deal of information is related to a station’s location, its identifiers, the surrounding topography, and the organizations and people involved with the station. Basic station metadata include: CRN station ID; identifiers assigned by other networks (COOP, WMO, etc.); station name and aliases; latitude and longitude in decimal degrees, from GPS; elevation above mean sea level; geographic location data, including physical address, nearest major city, county, climatic division, state/province, etc.; driving instructions to station, with maps; site survey, including layout and exposure of instrumentation, and location of buildings, trees, etc.; soil type; vegetation types and condition; digital images, including digital photos (surface in octants, fisheye view of sky above station, etc.), LANDSAT imagery, and aerial imagery; involved parties and agencies, including landowner and CRN partner, with contact information; information on nearby stations in other observation networks (ASOS, COOP, WBAN, etc.); and notes.

Station Instrumentation and Maintenance

While a particular model of instrument has a known set of design characteristics, each individual instrument has unique characteristics. Information related to the instrumentation installed at each station, including recommended, scheduled, and performed maintenance and calibration, is grouped here. Pertinent metadata items include instrument type; serial number; date of purchase; firmware revision; instrument location, if different from noted station location; instrument height above ground level; instrument exposure details; sampling interval; reporting frequency; recommended/scheduled maintenance and calibration procedures, including frequency; results of comparison with traveling standard (benchmarking); notes; and record of actual maintenance and calibration procedures performed, including instrument(s) being maintained, service type, agency, technician name, procedures used, date and time performed, readings/values/objective measurements, completion status, necessary follow-up (type, date, and responsible party), and technician’s notes.

Instrument Specifications and Service Procedures

This category comprises information regarding instrumentation (applicable regardless of where the instrument is installed), such as instrument specifications, instructions, reference values, and diagrams for any maintenance or calibration procedures performed on the instruments. Metadata tracked for each instrument or sensor include manufacturer; model; phenomena measured (temperature, precipitation, wind speed, etc.); how the instrument functions; sampling interval range; measurement range; resolution; accuracy; digital images, including photos, diagrams, and scanned copies of specification sheets; and service schedule and details, including service type (installation, preventive maintenance, calibration, etc.), procedure description, standard values, required expertise and equipment, and schedule/frequency.
Pre-transmission Sampling and Averaging Procedures
After an instrument makes an observation, the recorded value may undergo processing before transmission. Metadata related to the data sampling and processing procedures before transmission include procedure description; frequency; algorithms; software and hardware used, including version information; input source (instrument, element, etc.); and special notes.

Data Transmission System and Procedures
Some form of data transmission system, data formats, and procedures will be used to transfer the observations to the point of ingest. Among the transmission-related metadata of interest are method of transmission, external communication identifiers (such as handbook 5 [SHEF]) identifiers, data format transmitted, transmission frequency, time standard, transmission time, hardware and software used, equipment maintenance logs, and involved parties/agencies.

Data Handling
This subject area describes ingest, processing, quality control, and archiving of observations. Often the only definitive source for the rules and transformations used is the application source code itself. Algorithms, procedures, specifications, and the like may be documented via freeform text, documents, diagrams, or scanned images. The system will track these documents, along with their version history, and provide a link to each. This approach should be much quicker and less expensive than completely decomposing and integrating this information into the database as discrete data fields. Metadata elements of interest include quality control and conversion procedures and algorithms, constants and parameter values, processing and storage systems, locations, significant changes to observations, and involved parties/agencies.

Derivative Data Products
A variety of data products may be derived from the basic observations, each with its specific details. If the standard documentation for the data product contains all the required information, that documentation will be used. Product details include systems, procedures, algorithms, and values used in production of the data product; description; period of record; geographic coverage; data elements; product media and format(s); inventory and location of the product; and access systems.

Network Administration Information
This category includes details regarding the administration of the CRN, including network ownership, partners, documentation, and all other information pertaining to the network as a whole. Examples are: controlling agency, supporting agencies, program manager(s), contact information, defining documentation, legislative authorizations, manuals, training material, and database manager contact information.

Future Opportunities
The CRN provides an opportunity for interagency cooperation and leveraging of resources that is unprecedented in the history of U.S. climate monitoring. In fact, a coordinated effort is crucial to its success. A joint effort can minimize the cost of establishing and
operating the CRN while maximizing the benefits and information obtained from the network. Coordination at the federal level is occurring at all of the project's stages: development and design of the system, procurement and evaluation of candidate instrumentation, installation and maintenance of the equipment, monitoring and data evaluation, and utilization of the data. The CRN system is being designed for future expansion, with data logger ports available to NOAA and other agencies for attaching additional sensors (e.g., USDA evaporation in addition to soil moisture and soil temperature [mentioned earlier]; NSF and DOE trace gas; NWS humidity and atmospheric pressure, etc.). As an inter-agency network, the data will have application to weather forecasting, agriculture, hydrology, and commercial interests, among others, in addition to its primary purpose of operationally monitoring climate anomalies and detecting climate change.

The CRN is part of a multiyear NOAA climate initiative to modernize the COOP network and create a network that meets the GCOS standards for long-term climate monitoring. The first fiscal year of the CRN project is focused on acquiring core sensors for about half a dozen stations, performing laboratory calibrations to ensure each sensor is within design specifications, and conducting a local field test in which the stations are placed in close proximity. The purpose of this test is to demonstrate that each data measurement, collection, and transmission system functions as expected. So that station intercomparisons can be carried out with the same local meteorology, the test site must have an extended flat surface with low uniform vegetation and open exposure from all directions. When it can be demonstrated that the sensors and system components are performing satisfactorily, the stations will be relocated to pre-selected sites for the validation phase.

The purpose of the validation phase is to compare measurements of temperature and precipitation from the CRN stations with those from nearby or collocated HCN stations and to provide an assessment of overall station performance. The HCN stations must be selected to encompass the range of climates across the United States, including Alaska and Hawaii. The length of the validation phase should be a minimum of 9 months so that the extreme seasons, typically summer and winter, are included. Thus this phase will continue into the second year of the project. Each station that successfully completes the validation phase will be commissioned as an official member of the U.S. CRN.

As funding becomes available, additional stations will be introduced into the CRN after sensor calibration, local field testing, and validation. Thus, completion of the CRN project is a multiyear effort.

**Acknowledgments**

The authors would like to acknowledge the contributions of the many CRN team members, including David Easterling, Michael Helfert, Andrew Horvitz, Kenneth Hubbard, Michael Janis, Robert Leffler, Thomas Lockhart, David Mannarano, Robert Quayle, Kevin Robbins, Glenn Rutledge, and Garry Schaefer.

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Data Collection, Processing, and Quality Control for MesoWest

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Abstract

MesoWest—Cooperative Mesonets in the Western United States—is a program to improve weather observing capabilities in the western United States. Meteorological data are collected in real time, processed into a common database, assessed provisionally for quality, and made available in near real-time and via a long-term archive for operational, research, and educational purposes.

Introduction

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 addition, the National Weather Service (NWS) Western Region specifically is interested in improving the use of observational networks, such as mesonets. The NOAA Cooperative Institute for Regional Prediction (CIRP) has developed software to link together weather observations from more than 2100 stations in the western United States in addition to those in the NWS/FAA network (Figure 1). We refer to this collection of regional and local networks as MesoWest. Real-

Figure 1. Location of roughly 2100 weather observing stations (black asterisks) in the western United States that are accessible via MesoWest. Triangles denote the locations of approximately 350 NWS/FAA stations.
time and archival data and information regarding MesoWest can be obtained through the Internet at http://www.met.utah.edu/mesowest.

MesoWest Cooperating Agencies
MesoWest collects and processes meteorological data from more than 40 participating organizations with networks of varying size. Individual observation stations often represent cooperative ventures between several organizations. Significant recent additions to MesoWest include the extensive networks managed by the Bureau of Reclamation (Remote Automated Weather Stations [RAWS]) and the Natural Resources Conservation Service (Snowpack Telemetry [SNOTEL]). Table 1 is a listing of the current MesoWest data providers; efforts continue to bring additional meteorological networks into the project.

Data Collection and Processing
MesoWest participants provide data via the Internet to CIRP. We have developed software to process the varying data formats into a common database. Additionally, staff from the Salt Lake City NWS and CIRP help maintain and collect data from a local network of sensors (referred to as SNOWNET) with the use of phone and radio communications. These data are also transmitted to CIRP from the Salt Lake City NWS via a T-1 line. Data collection intervals from MesoWest participating networks vary from several hours to 15 minutes. Data resolution spans from hourly averages to 5-minute averages.

MesoWest processing operates on a 15-minute cycle. At the end of each processing cycle the integrated data are entered into an SQL database, and the data are also made available in real-time via a web interface and through data files available on an ftp server.

Data types processed into the MesoWest database include: air temperature, dew point, relative humidity, atmospheric pressure, wind speed, wind direction, wind gust, precipitation, snowfall, snow depth, solar radiation, and soil-related variables such as soil temperature. Given the variety in data providers, each site, even within individual networks, will have a unique set of sensors available that are a subset of those listed above.

Real-time Data Quality Control
Using data collected from many different networks with heterogeneous sensors, siting, standards, and maintenance procedures is not without problems. Quality control procedures have been implemented to assess temperature, dew point temperature, and pressure based on statistical regression schemes (Splitt and Horel, 1998). Figure 2 depicts the average daily difference between reported temperature observations and statistical estimates of the temperature at the site locations. Advanced quality control algorithms for wind and precipitation remain to be developed. Presently, we define a single quality control flag for an entire set of observations recorded at a site for a given time. We intend to define the quality of the data from each sensor separately and disseminate the quality control information in a manner that is useful to operational users of the data.

Quality control procedures implemented on the MesoWest data make it possible for these data to be incorporated into national operational and research modeling activities. For example, MesoWest data are already being incorporated into regional analyses at Western
Table 1. Participating members of MesoWest—Cooperative Mesonets in the western United States, as of February 2000.

<table>
<thead>
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<th>MesoWest participating organizations</th>
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**Regional networks accessible via the Internet**
- AGRIMET—U.S. Bureau of Reclamation (Idaho, Montana, Washington)
- RAWS—Bureau of Land Management and National Interagency Fire Center (western states)
- SNOTEL—USDA National Resources Conservation Service (all western states)

**Sub-regional networks accessible via the Internet**
- ARL—FRD—Field Research Division (Idaho)
- ARL/SORD—Special Operations and Research Division (Nevada)
- Campbell Scientific (Utah)
- Central Utah Water Conservancy District
- Clark County Flood Control District (Nevada)
- Colorado Basin River Forecast Center (Arizona, Colorado, Idaho, Nevada, Utah, Wyoming)
- Desert Chemical Depot (Utah)
- Dugway Proving Grounds (Utah)
- Emery Water Conservancy District (Utah)
- Flood Control District of Maricopa County (Arizona)
- Montana Department of Transportation
- Nevada Department of Transportation
- Sevier River Water Users Association (Utah)
- Ski Resorts: Alta, Utah; Jackson Hole, Wyoming
- Utah Department of Transportation
- Tooele County Emergency Management (Utah)
- Wyoming Department of Transportation

**Data collected via radio links or telephone (primarily in Utah)**
- Judd Communications
- National Park Service
- NWS Salt Lake City Forecast Office
- PacifiCorp
- University of Utah
- U.S. Fish and Wildlife Service
- Utah Division of Air Quality
- Utah Avalanche Forecast Center
- Utah Department of Natural Resources
- Utah Department of Transportation
- Ski Resorts—Beaver Mountain, Big Sky and Bridger (Montana), Brighton, Deer Valley, Park City, Snowbasin, Snowbird, Solitude, Sun Valley (Idaho), Sundance
Figure 2. A histogram of the average daily difference between statistical estimates of the temperature and observations of temperature at MesoWest stations. Most data falls within a few °C of the statistical estimates. Questionable data can be identified by using the differences as a selection criteria.

Region Forecast Offices through the use of the MAPS Surface Assimilation System (MSAS), which is under development at the Forecast Systems Laboratory.

Data Access and Web Server
Real-time data access to MesoWest data streams is accomplished with a web-based interface and by files accessible through an anonymous ftp server. Archival data are accessible only via the web-based interface, which pulls data from an MySQL database. Figure 3 depicts the entry into the public interface designed for general access to the data. Users are able to view station listings by selecting geographical locations beginning at the state level and continuing to the county level. After an individual site is chosen, tabular listings, times series graphics, or multiple station area plots can be generated. Figure 4 is a sample of a real-time tabular listing of data from a MesoWest site. Archival data are available for many sites from January 1997 through the present.

Operational and Research Uses
MesoWest data are used extensively for operational forecasts by meteorologists at local NWS offices in the western United States and by the Storm Prediction Center in Norman, Oklahoma. A survey of NWS Science and Operations Officers (SOOs) in the Western Region indicated that many of the offices use the data extensively. MesoWest provides forecasters with the ability to monitor extreme weather situations and improve protection of life and property.

As a result of collaborative efforts with the NWS Western Region Scientific Services Division staff, the MesoWest data are disseminated every 15 minutes to all NWS offices in the Western Region through the region’s Wide Area Network and are also available for use by other entities, such as national centers or offices in other regions, via the Internet.
Welcome to MesoWest!

To begin, click on a state on the accompanying map...

Use of the weather and climate information provided by MesoWest is subject to the following restrictions.

Figure 3. The public web page interface to MesoWest data.

Conditions for ANTELOPE ISLAND S.P. (SNOWNET)

<table>
<thead>
<tr>
<th>Conditions: April 11 – 14:30 (mt)</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Current</th>
<th>Today's Max</th>
<th>Today's Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>15.6°C</td>
<td>15.6°C at 14:30</td>
</tr>
<tr>
<td>Dew Point</td>
<td>3.1°C</td>
<td>8.9°C at 02:00</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>43%</td>
<td>93% at 02:00</td>
</tr>
<tr>
<td>Wind</td>
<td>2.21 m/s at 301°</td>
<td>4.0 m/s at 01:15</td>
</tr>
<tr>
<td>Gust</td>
<td>4.01 m/s</td>
<td>5.4 m/s at 13:00</td>
</tr>
<tr>
<td>Total Precip</td>
<td>0.00 cm</td>
<td></td>
</tr>
</tbody>
</table>

Time Series

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Temp</th>
<th>Dvpt</th>
<th>Relh</th>
<th>Wind</th>
<th>Drct</th>
<th>Gust</th>
<th>Precip</th>
<th>Snow</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/11</td>
<td>14:30</td>
<td>15.6</td>
<td>3.1</td>
<td>43</td>
<td>2.21</td>
<td>301</td>
<td>4.01</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>04/11</td>
<td>14:15</td>
<td>15.0</td>
<td>3.2</td>
<td>45</td>
<td>2.68</td>
<td>314</td>
<td>4.01</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>04/11</td>
<td>14:00</td>
<td>15.0</td>
<td>4.1</td>
<td>48</td>
<td>2.21</td>
<td>321</td>
<td>4.01</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>04/11</td>
<td>13:45</td>
<td>15.0</td>
<td>3.2</td>
<td>45</td>
<td>2.21</td>
<td>302</td>
<td>4.01</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>04/11</td>
<td>13:30</td>
<td>15.0</td>
<td>3.5</td>
<td>46</td>
<td>1.80</td>
<td>304</td>
<td>3.60</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>04/11</td>
<td>13:15</td>
<td>14.4</td>
<td>4.7</td>
<td>52</td>
<td>2.21</td>
<td>325</td>
<td>4.94</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>04/11</td>
<td>13:00</td>
<td>14.4</td>
<td>5.0</td>
<td>53</td>
<td>2.68</td>
<td>312</td>
<td>5.35</td>
<td>0.00</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 4. An example of a tabular listing of real-time meteorological data using the MesoWest web-based tools.
Figure 5. Analysis of surface temperature (shading in 0F) at 2 km resolution at 1500 UTC 21 March 2000 using the ARPS Data Analysis System. Objective analyses of this type are created regularly using MesoWest data.

Our efforts are complementary to and rely on the Local Data Acquisition and Dissemination (LDAD) software available on the Advanced Weather Interactive Processing System (AWIPS); we assist forecast offices by providing a data stream of local observations in a format that can be directly ingested into AWIPS through LDAD.

In addition to the use of the individual station data, CIRP creates objective analyses of meteorological data fields from the array of stations available in real-time. Surface analyses of such fields as the temperature, dew point, and pressure are generated in near real-time. Other types of analyses are generated by combining the MesoWest data streams with atmospheric model output, or by running algorithms directly on the data. These types of analyses are being used to aid operational forecasting (Figure 5).

**Future Network Coordination**

Now that the feasibility of our approach to enhance the observational system has been demonstrated through its use in field offices throughout the NWS Western Region, we intend to identify and seek participation from additional networks available in the western United States. The California Data Exchange is an example of an extensive network of primarily precipitation sensors in California. In addition to existing networks, the Federal Highway Administration is fostering expanded state Road Weather Information
Systems (RWIS). We have already been in contact with representatives of state transportation departments from all western states except California, Colorado, and New Mexico. In addition to the RWIS data already being obtained from Montana, Wyoming, Nevada, and Utah, we expect to obtain access to weather sensors in Idaho and Arizona within the next year. Other sources of weather information around the western United States to be identified include state and local air, water, and agricultural agencies; alert networks; military installations; and commercial firms such as ski areas. We anticipate that there are at least another 2000 automated weather stations in the western United States that could be accessed in real time.

References
The Nebraska and High Plains Regional Experience with Automated Weather Stations

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Abstract
The High Plains Regional Climate Center (HPRCC) was established in 1987 and is one of six regional centers providing climate services to the continental United States. HPRCC is located at the University of Nebraska in Lincoln. HPRCC’s mission is to carry out applied climate studies to aid in the development of improved climate products for use in an array of climate services, including data collection, analysis, and dissemination in the HPRCC region. This chapter describes the Automated Weather Data Network (AWDN) and the interfaces that provide near real time climate services with emphasis on ET or crop water use. Automated weather stations are monitored daily at 148 locations in ten states. Data are subjected to quality assurance testing and made available to the public. AWDN data are merged with a stream of data that includes the cooperative network data and historical data dating to the 1800s. Queries by the public to the subscription-based online interactive system are approaching 250K per month while queries to the HPRCC web site are about 100K per month.

Introduction
Regional Climate Centers (RCCs) were established in response to the need to improve climate services at the local, state, and regional levels (Changnon et al., 1990). One of the fundamental challenges for RCCs is to advance the provision of climate information for the nation’s economic, governmental, and social sectors. To read more about RCCs and for contact information, refer to these web sites:

- High Plains RCC http://hpccs.unl.edu/
- Midwestern RCC http://mcc.sws.uiuc.edu/
- Southeast RCC http://water.dnr.state.sc.us/climate/sercc/
- Southern RCC http://www.srcc.lsu.edu/
- Western RCC http://www.wrcc.dri.edu/

Together with the state and federal offices, these entities form a three-tiered climate services system. More information about the national level can be obtained from the National Climatic Data Center’s web site: http://www.ncdc.noaa.gov/.

Several major requirements must be addressed in order to improve climate services. First, an adequate data collection system is needed to monitor critical variables at an acceptable sampling and delivery frequency. Second, quality control (QC) and analyses (QA) are necessary. The QC and QA, when linked to a quick-response maintenance and repair
capability, will ensure complete and accurate data for use in summaries and products. Third, regular client feedback (surveys, advisory committees, etc.) will establish the needs of decision makers and resource managers in the targeted sector of the economy. It is essential that the interfaces serve the general meteorology and climatology communities, so that the private sector can develop and deliver value-added products. In some cases, applied research is needed to develop models and other technological tools for the purpose of relating the current climate situation to the area of interest (agriculture, water resources, energy, transportation, recreation, etc.). Another requirement is adequate technology to deliver the summaries and products in a timely manner.

The use of electronic equipment to automate the collection of measurements from weather-related sensors at remote sites has ushered in a change in the ability to collect weather data (Hubbard et al., 1983; Howell et al., 1984; Tanner, 1990). The advances in the field of data collection found their way into the National Weather Service (NWS) program of modernization, as more than 1000 ASOS (Automated Surface Observing System) weather stations were installed over the past decade (ASOS, 1988). The NWS also plans to modernize the cooperative observer network. Automated state and private networks have been developed, and a recent survey determined that these networks comprise more than 600 weather stations.

Communication and computer technology have greatly increased the ability of climatologists to monitor and disseminate the important characteristics of climate. RCCs are institutions that engage in applied research necessary to improve climate products, including crop water use estimates.

**Data Collection**

Automated weather stations are maintained at 148 locations in the ten-state region (Colorado, Iowa, Kansas, Montana, Minnesota, Missouri, North Dakota, Nebraska, South Dakota, and Wyoming). These stations collect hourly data for variables known to be of importance to agricultural crop and livestock production, including air temperature and humidity, soil temperature, precipitation, wind speed and direction, and solar radiation. A computer calls each station beginning at 1 A.M. The data for the previous 24 hours is downloaded, quality controlled, and archived for use by the HPRCC system. A telephone line or a cell phone is installed at each site. A flow diagram is shown in Figure 1. Software and system components were developed for this system (Hubbard et al., 1983).

Weather stations at remote sites monitor sensors every 10 seconds and calculate the hourly averages and, where appropriate, totals. The minimum set of sensors is shown in Table 1.

The installation heights shown are standard for AWDN stations. Other recommendations for standards have been put forth by the World Meteorological Organization, the United Kingdom Meteorological Office, and the National Weather Service. For these standards and those of other Automated Weather Networks in the United States, see Meyer and Hubbard (1992).

The AWDN has grown from 5 stations in 1981 to 148 stations in 2000. Much of the initial growth was due to the interest of researchers who were operating digital weather stations
Table 1. Sensor installation, accuracy, and sampling information.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Variable</th>
<th>Installation ht.</th>
<th>Accuracy</th>
<th>Hourly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermistor</td>
<td>Air temperature</td>
<td>1.5 m</td>
<td>0.25°C</td>
<td>Avg. °C</td>
</tr>
<tr>
<td>Thermistor</td>
<td>Soil temperature</td>
<td>-10 cm</td>
<td>0.25°C</td>
<td>Avg. °C</td>
</tr>
<tr>
<td>Si cell</td>
<td>Radiation–global</td>
<td>2 m</td>
<td>2%</td>
<td>Flux (W m⁻²)</td>
</tr>
<tr>
<td>Pyranometer</td>
<td>Wind speed</td>
<td>3 m</td>
<td>5% (0.5m/s start-up)</td>
<td>Total passage (ms⁻¹)</td>
</tr>
<tr>
<td>Cup anemometer</td>
<td>Wind direction</td>
<td>3 m</td>
<td>2°</td>
<td>Vector direction</td>
</tr>
<tr>
<td>Wind vane</td>
<td>Wind direction</td>
<td>3 m</td>
<td>2°</td>
<td>Vector direction</td>
</tr>
<tr>
<td>Coated circuit</td>
<td>Relative humidity</td>
<td>1.5 m</td>
<td>5%</td>
<td>Avg. (%)</td>
</tr>
<tr>
<td>Tipping bucket</td>
<td>Precipitation</td>
<td>0.5 to 1 m</td>
<td>5%</td>
<td>total (mm)</td>
</tr>
</tbody>
</table>

Figure 1. The flow of data through the automated weather network.
without the benefit of telecommunication or a data management system. Beginning in 1983, the AWDN began to include sites from surrounding states. As time passed, the private sector became interested in adding stations. Resource management agencies also have an active role in purchasing and supporting stations in the network. One unique class of weather station sponsor is the community consortium. In this case a number of interested parties from a community (e.g., agri-chemical dealers, farm elevators, radio station, public power agency, etc.) agree to share in the expense of purchasing and maintaining a station.

The 148 stations in the network are distributed in the region represented by the High Plains Regional Climate Center as follows: Colorado 4, Iowa 12, Kansas 16, Missouri 2, Minnesota 5, Montana 2, Nebraska 51, North Dakota 44, South Dakota 11, and Wyoming 1. The station locations are plotted in Figure 2. In general, each state is responsible for maintaining its weather stations, and the states with larger numbers of stations run an in-state system to serve clientele within the state’s boundaries. The High Plains Regional Climate Center calls these stations once each day in the early morning hours to download data.

Figure 2. Location of stations in the Automated Weather Data Network.
Maintenance is an important and costly activity. Replacement of sensor components includes bearings in the cup anemometer on a 2-year cycle. Relative humidity sensors are calibrated on an annual cycle. The potentiometer on the wind vane is replaced as needed. The tipping bucket is checked for level and calibrated each year by using the volume-to-mass relationship for a known amount of water. Leveling screws are adjusted if needed in order to obtain the correct number of tips. Certain sensors are removed from service for calibration. The silicon cell pyranometers are calibrated as a group against an Eppley Precision Spectral Pyranometer (Aceves-Navarro et al., 1989). In a similar manner, anemometers can be calibrated against a “secondary standard.” Thermistors and humidity sensors can be calibrated directly under controlled conditions. Devices like dry block calibrators and dew point generators are useful for this purpose.

Average annual costs associated with each site include: local telephone service ($480), telephone calls ($180), travel ($200), repair costs ($100), replacement costs ($100), and labor ($1250). The total costs are about $2310 per year, but this cost does vary with the number of stations, distance to stations, and other local rates.

Data Management and Applications Programs

A tremendous amount of data can be generated with an hourly weather network. The High Plains network produces about 1 Mb of data annually for any three stations. If these data are to be used effectively, they must be easy to access. Thus, data management is a real concern. In the case of the High Plains network, the approach has been to develop a data management system written entirely in FORTRAN (Hubbard et al., 1992). This system is indicated as the database component in Figure 1.

A suite of utility programs includes tools for data management, quality control, data retrieval, and station selection. Applications software includes programs (see Figure 1) to analyze data and produce summaries for any variable over any desired time period. Summaries include temperature, precipitation, heating and cooling degree days, growing degree days, evapotranspiration, leaf wetness, soil water, and crop yield.

On the HPRCC Internet site for online subscribers, a crop water use report may be generated by selecting inputs from the screen depicted in Figure 3. The user is able to choose any combination of crops, maturity groups, and emergence dates.

An example of the ET product is shown as it would appear on the computer screen (see Figure 4).

Research Network

The High Plains Automated Weather Data Network has served as a source of data for both research and service efforts. Some of the research aspects will be covered in this section and the service aspects will be covered in the following section.

Evaporation (ET) at the earth’s surface is a major component of the hydrological cycle and is critical to irrigation scheduling from a water balance approach. Research in the
Figure 3. Input specification screen for the ET product.

Figure 4. Format of the ET product from the online system.
area of evapotranspiration has included efforts to identify the effect of random and systematic errors in measurements used to calculate potential ET as well as efforts to improve the projections of potential ET (Meyer et al., 1989). The AWDN has also been essential to determining appropriate limits for potential ET in the very arid parts of the High Plains region (Hubbard, 1992).

Monitoring of drought conditions is another research focal point. Robinson and Hubbard (1990) and Camargo and Hubbard (1994) evaluated the potential use of network data in the assessment of soil water for various crops grown in the High Plains. A Crop Specific Drought Index (CSDI) for corn has been developed and tested (Meyer et al., 1993a and 1993b). Results from the studies indicate that the CSDI for corn will be valuable when applied to drought assessment (Meyer et al., 1993a and 1993b). A CSDI for sorghum (Camargo and Hubbard, 1999) is also under development.

Accuracy of interpolation between stations in a network is a topic of research. The spatial interpolation of potential ET (Harcum and Loftis, 1987) was examined using AWDN data. On a related topic, the AWDN data were used to examine spatial variability of weather data in the High Plains (Hubbard, 1994). Another study examined whether it is better to interpolate the weather variables for computing potential ET at a site or to interpolate the potential ET calculated at the surrounding stations (Ashraf et al., 1992).

The AWDN system has been used to collect basic meteorological data for various field experiments (e.g., Hubbard et al., 1988). Data taken by the system are also being used in urban water use studies and in Project Storm.

**Service Network**

**Self-Service Access**
The HPRCC staff developed an online Internet system for users which features interactive use of the entire historical archive of the HPRCC. A revised system was released on May 1, 1996, and users of the former RBBS were invited to subscribe to the new system. Access to the new system increased from approximately 2000 in 1996 to 250000 per month in 2000.

Digital data disseminated by the HPRCC from the new system can be redistributed several times to larger audiences. A clear example is Data Translation Network (DTN). DTN, a private company, accesses HPRCC’s evapotranspiration, soil temperature, heating degree data, and other reports, which they broadcast to a network of subscribers. Paid subscribers to DTN are able to view this current information on their TV screen. They choose the pages they wish to view by simply indicating an index number on a push button pad supplied by DTN. More than 100000 clients subscribe to DTN.
Online Access System
The new online system offers both opportunities and challenges. The positive features of
the system are:

• it is accessible via the web
• it has the computing power of a work station
• clientele have online access to the historical data archives, which date to the late
  1800s
• users can make general summaries according to their own specifications
• up-to-date data are available for decision makers who require it
• an autopilot feature allows users to schedule future summaries, saving the time other-
  wise required to log on and re-create the summary
• information delivery is automated, by e-mail or ftp
• it has greater simplicity of interface
• the learning curve is decreased
• it can be navigated by “mouse” point-and-click

Home Page
The HPRCC home page committee designed a new home page (http://hpccsun.unl.edu).
The number of direct accesses to the home page has reached 100000 per month.

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Climate Research 2:(3).

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Preliminary Findings of the 1999 Survey of (Nonfederal) Automated Weather Stations in the United States and Canada

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World Agricultural Outlook Board, Washington, D.C.  
Kenneth G. Hubbard  
High Plains Regional Climate Center, University of Nebraska, Lincoln

Abstract
Over the past 20 years, a significant number of automated weather networks have been established. These systems are independent from those operated by federal governments. This study is an update of a 1992 survey that was conducted to identify new networks and gain information on their operating mechanisms. Survey forms were mailed to the participants of the 1992 survey, as well as those identified as being potentially involved with newer networks.

According to the preliminary responses, the automated networks tend to adhere to standards for instrumentation, including calibration and routine maintenance. However, differences arise in data quality control procedures, with more than 10% of respondents reporting no action taken when errors were detected. Three-quarters of the respondents supplied data to the public, more than half of it without cost. Most networks processed data on a fairly timely basis but dissemination avenues and formats varied greatly. The greatest challenges faced by the operators included quality control, standardization of both data and equipment, and achieving sustainable funding.

The majority of the network operators that responded expressed a willingness to participate in future activities, including joint products, a national network registry, and network symposia. The authors believe that this cooperation will be vital in ensuring the sustainability of current and future networks.

Introduction
In the United States and Canada, the number of nonfederal, automated weather networks (AWN) has steadily risen since 1980. This rapid growth is the result of the increased need for meteorological information not readily available elsewhere. Insufficient station density, timeliness of data availability, and amount and type of information available are challenges faced by users in research and operations sectors that depend on this type of information, and many institutions have begun to collect information to meet their data needs. These needs are especially critical in the field of agriculture (Elliot et al., 2000), where real-time observations of parameters other than the standard rainfall and temperature are vital in decision making.
In the early 1990s, Meyer and Hubbard (1992) conducted a survey of nonfederal AWNs in the United States and Canada. The objectives of the survey were to (1) determine the number and location of stations within the networks; (2) determine the type of measurements taken; and (3) learn more about operating procedures and data uses.

A new survey conducted in 1999 sought to update the information gathered in the previous survey, but with an increased emphasis on data dissemination and public services. The goals of the 1999 survey were to (1) identify new networks; (2) identify new users and others interested in obtaining weather data; (3) identify the concerns of network operators; and (4) create a forum for the exchange of ideas and information, including collected data.

This chapter represents a preliminary summary of the initial responses of the survey as presented at the Automated Weather Station Workshop in Lincoln, Nebraska (March 2000).

Methodology

Using the original mailing as a guide, a new survey form was developed to gather updated information on the AWNs, with an increase in the areas of information processing and public service. The questions fell into one of four basic areas:

1. General information and mechanisms.
2. Data management issues.
3. Data dissemination and services.
4. Considerations for the future.

The 1992 questionnaire was mailed to a group that included subscribers to The Tripod (a newsletter published by the High Plains Regional Climate Center), experiment station directors at all land grant universities, and persons identified as having experience with AWNs. This mailing list was reused for the 1999 survey and was augmented by contact information provided by state climatologists, state Departments of Natural Resources, program directors at land grant universities, and the Nuclear Utility Meteorological Users Group (NUMUG).

Those receiving the survey were requested to forward the survey to someone in their state if they themselves were not involved in operating an AWN. More than 600 surveys were mailed out over a 2-week period. In addition, an Internet web site was developed whereby respondents could record their answers online.

Results

General Information and Mechanisms

a. History—Of the 39 networks responding at the time of publication, 33 have been in operation for less than 20 years, and 15 came into existence since the last survey (Figure 1).
b. *Basic Operations*—The authors included questions regarding staffing support for the networks. The intent was to determine which AWNs were “fully staffed” and which were operated using part-time help or volunteers. The answers came in two distinct categories: those listing general positions within the network, and those identifying the level of expertise of the employees (Tables 1 and 2). Four respondents acknowledged that they were the only ones involved in their network’s operations.

c. *Partnerships*—Nearly all of the respondents indicated some type of partnerships with private industry and/or universities. However, many also identified some type of relationship with the public sector as well. Of the networks offering valid responses, 12 indicated some type of arrangement at the federal or national level, and 15 had relationships at the state, provincial, or municipal level (NOTE: respondents were included in both categories where appropriate).

**Table 1. Staffing by title.**

<table>
<thead>
<tr>
<th>Positions</th>
<th>Networks responding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Administrative</td>
<td>10</td>
</tr>
<tr>
<td>Maintenance</td>
<td>21</td>
</tr>
<tr>
<td>Information systems</td>
<td>14</td>
</tr>
<tr>
<td>Secretarial</td>
<td>2</td>
</tr>
</tbody>
</table>

**Table 2. Staffing by expertise.**

<table>
<thead>
<tr>
<th>Positions</th>
<th>Networks responding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteorologist/</td>
<td>7</td>
</tr>
<tr>
<td>hydrologist</td>
<td></td>
</tr>
<tr>
<td>State climatologist</td>
<td>1</td>
</tr>
<tr>
<td>Chemist/engineer</td>
<td>3</td>
</tr>
<tr>
<td>Students/faculty</td>
<td>9</td>
</tr>
<tr>
<td>Volunteer</td>
<td>2</td>
</tr>
</tbody>
</table>

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Nearly a third of the AWNs are provided with staff as a result of these partnerships. Equipment purchases and siting considerations are also affected by cooperative efforts. Only about 10% of the networks reported outright ownership of stations, and none reported landownership (Figures 2 and 3).

Figure 2. Station ownership.

Figure 3. Land ownership.
d. *Individual site information*—Questions about the placement criteria for stations within the network were designed to determine not only the purpose for those particular stations but also whether logical decisions were made during the site selection process. Figure 4a lists the percentages of those networks that took into account key features that potentially could have affected observations at a particular site. Figure 4b breaks down the “other” responses, or those written in by the respondents. Of those giving other reasons, just over 60% indicated that the networks were designed for a specific purpose and that the stations were sited accordingly. Nearly 20% chose sites based on access to phone and electrical lines. Property availability and the desire to fill in areal gaps in coverage each accounted for about 8% of the responses. One network indicated that each county had to house at least one station.
Underlying surfaces at stations were typically natural cover, grass, or alfalfa (81% of stations documented).

Metadata was also variable among the responding networks. Table 3 shows the breakdown of the types of information available at individual sites above and beyond name and cursory location information. It is interesting to note that more than half of the networks are making use of new technology like Global Positioning Systems (GPS) and digital photography. However, only about one-quarter of them archive information on local soils or vegetation, which would be helpful in agricultural applications.

Table 3. Site records metadata.

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil profiles</td>
<td>25.6</td>
<td>74.4</td>
</tr>
<tr>
<td>Site photos</td>
<td>70.7</td>
<td>29.3</td>
</tr>
<tr>
<td>GPS readings</td>
<td>51.2</td>
<td>48.8</td>
</tr>
<tr>
<td>Local vegetation</td>
<td>22.5</td>
<td>77.5</td>
</tr>
<tr>
<td>Environmental changes</td>
<td>41.5</td>
<td>58.5</td>
</tr>
</tbody>
</table>


e. Equipment—The main observations taken by the AWNs included liquid precipitation, temperature, humidity, wind speed/direction, solar radiation, and sea level pressure. Height placements were generally within the range prescribed by the WMO (Doorenbos, 1976). Less common observations included weather depiction (available from 23% of the networks), snow depth (17%), sky conditions (9%), and current weather (39%).

f. Data Retrieval—Most data is recorded in at least hourly intervals, with some networks recording observations at 5-minute intervals. As seen in Figure 5, about 40% of the observations were on daily intervals. These included daily solar radiation totals and daily liquid precipitation at automated rain gauges.

Data retrieval from the individual stations to a central processing center is undertaken in a number of ways, with many networks employing more than one method. Not surprisingly, most observations are transmitted via land phone lines (Figure 6). However, nearly 40% of the AWNs use cellular phones, a relatively new but growing technology. In contrast, more than 15% of the networks rely on site visits to download information from the data loggers. Line-of-site radio and satellite transmissions are also used by some networks. Other modes of data retrieval include meteor burst, a 2-way communication mode whereby a signal is bounced off of an ionized dust layer high in the earth's atmosphere (NRCS 1997), and radio transmission performed on dedicated frequencies.

Data Management Issues

a. Database Management Software—Nearly three-quarters of the networks reported using a formal database management system. These systems were evenly divided between commercial and proprietary, or in-house, software. The completeness of the database ranged from a low of 56% to nearly 100% with an across-network average of 92%.
Figure 5. Observation recording frequency.

Figure 6. Data retrieval methods.
b. *Turnaround for Availability*—Of 29 valid responses, 14 reported data availability of one hour or less (Figure 7). Seven networks reported that at least a portion of their data was not available for use for at least one month.

c. *Staffing*—Just under 30% of the responding networks employ a full-time database manager. About 21% of the networks have full-time staff dedicated to quality control, with the remaining networks reporting that other staff devoted at least part of their time to quality control activities.

d. *Data Quality Control*—In the event of an identifiable error, about 82% of the data is corrected in some manner (Figure 8). That compares with about 13% of the data that are neither corrected nor flagged. This was one of the more surprising results, considering the importance of the information and the presumed ability of networks to be able to edit their own data.

Figure 8. Quality control actions taken.
e. Equipment-Oriented Quality Assurance—Most of the networks reportedly follow a fairly standard pattern of routine maintenance and instrument calibration. More than half of the networks perform calibration on an annual basis, with nearly all operations completed at least every 2 years. A few of the networks reported no calibration at all performed on pyranometers or anemometers.

About 56% of all calibration is performed by the AWNs, as opposed to being returned to the manufacturers. Of those conducting their own calibration, 4 did so on site and 11 returned the equipment to a laboratory or controlled setting. In addition, about one-fourth of the networks consult with the manufacturers on issues such as sensor design and required specifications. As a result of those consultations, specifications were met 80% of the time and sensors were redesigned 50% of the time.

Data Dissemination and Services
a. Dissemination Avenues—About 30% of the information is still provided by post (Figure 9). Not surprisingly, however, more than 80% of the data is available to the public via the Internet. Most other methods involve some type of standard link, telephone or otherwise, including FAX and FTP. Other avenues included e-mail and dissemination through other parties, including the Regional Climate Centers.

b. Available Products—Just over half (53%) of the data are made available to the public for free in some form (Figure 10). These formats ranged from raw/standard inputs (METAR or SHEF) to general reports and ASCII formats to program input. Less than 10% of the networks provide information in formats on a per-request basis. About 13% of the networks provide no free information to the public. Other products available to the public included models, forecasts, and special assessments.

![Figure 9. Dissemination avenues.](image-url)
Figure 10. Data available to public.

Figure 11. Data functions.

As depicted by Figure 11, more than half of the networks provide data to the public sector for research and public service activities. Interestingly, data is obtained by the private sector and kept internally for agency mission functions at about the same level. Just under 40% of the data that is freely available to the public is considered “real time” by the networks. Interestingly, this does not significantly differ from the turn-around time for data on a fee basis.

c. Partnerships (Community Outreach)—Nearly all of the responding networks reported some level of outreach to the public. In fact, about half of the networks provide information for educational purposes (see Figure 11). Typical examples of community outreach include Agricultural Expositions and extension services, schools (K-12 programs), farm-
ers and farm information hotlines, and services to homeowners and municipalities, including advice on lawn watering.

Public safety applications included forecasting, guidance to the Nuclear Regulatory Commission and the Canadian Avalanche Association, flood guidance, and discourse with law enforcement officials.

**Considerations for the Future**
The final section of the survey provided the respondents with an opportunity to state their concerns for the future of Mesonets. As seen in Figure 12, the greatest concerns were quality control issues and industry (or community) standards for both data formats and equipment. A source of sustainable funds was a close third.

![Figure 12. Challenges for the future.](image)

It was encouraging to note that user outreach was a significant concern, with a number of respondents wishing to discern the true utility of their products to the general public and expand their outreach.

Another encouraging sign was the willingness expressed by the networks to work together on mutually beneficial projects.

a. *National Products*—69% of the respondents were willing to provide information to a national net-based product.

b. *Mesonet Forums*—80% of the respondents expressed a desire to attend conferences or symposia on the subject of mesoscale networks.

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c. National Registry—88% of those responding were willing to provide information to a national Mesonet registry, accessible by the public as well as other networks.

Many of those answering NO to the above questions listed funding or agency mandate as a reason not to participate, which the authors consider an inability to participate rather than a fundamental disagreement on the goals suggested by such activities.

Conclusions and Recommendations

Based on the preliminary analyses of the responses to date, the authors are able to notice trends at the U.S. and Canadian AWNs. For example, although fairly autonomous, most networks have relationships with some level of government. In addition, most networks are still public service oriented and gear a portion of their products to that end.

The networks are operationally similar, with quality assurance and quality control practiced at a majority of the AWNs. However, the meta-datasets are highly variable, as would be expected with the wide range of purposes and inception dates.

Finally, most network managers are amenable to future collaborations for the purpose of sharing information and techniques.

The authors put forth the following recommendations:

1. The survey web site will be maintained so that new networks, and those that have not already taken part, may participate in the survey.
2. A national registry for mesoscale networks for the purpose of information exchange should be supported at a national level.
3. The development of reasonable operational standards should be encouraged.
4. Venues for peer review (symposia, conference sessions, etc.) should be identified and advertised.

References


Working Group Reports
Working Group A
Automated Weather Station (AWS) Network Coordination
at the State, Regional, and National Levels

Members: Christina Smith (CHAIR), Orivaldo Brunini, Radu Carcoana, Andrea Deho, Rainer Dombrowsky, Bart Freeland, Brad Martin, Greg McCurdy, Ron Paetzold, Hilton Pinto, Lineu Rodrigues, Bob Scott, and Michael Splitth

Working Group A developed the following rationale for collaboration:

1. More quality data and metadata is needed
2. Collaboration may lead to a standard and “certifiable” level for data
3. Greater economic benefits would accrue with wider “use” of the data
4. Unnecessary duplication would be eliminated
5. Smaller organizations allow for faster changes

Working Group A recommended that AWS workshop participants explore the following mechanisms for advancing the coordination of AWS issues:

1. Conduct, on a regular basis, AWS fora for interaction on such topics as AWS sensors, installation, maintenance, calibration, communications, data management, quality control, and applications.
2. Develop a list server and encourage group participation in discussions of AWN-related issues.
3. Develop a web page with links to descriptive information on existing networks, instructions on how to join the list server, and summaries of the AWS fora.
4. Discuss certification and standards to ensure high-quality data.
Working Group B
Communications with Weather Stations (and among Networks)

Members: Glenn Horton (CHAIR), Karl Blauvelt, Radu Caroana, John Gibbons, Ian Nichols, and Kevin Rhodes

Questions addressed by Working Group B on communications with weather stations were:

1. What are the current and emerging technologies?
   The various communication options are: telephone modems, cell phones (analog and digital), GOES satellite, MeteorBurst, spread-spectrum modems, wireless internet, NIC devices, internet/hard wire, RF, and field-based downloads (manual).

2. How do AWS managers stay current as technology moves the target?
   With regard to hitting the moving communications “target,” the group decided the most advantageous method to stay current would be to establish a “server link” among the people and organizations involved with AWS networks and their products. This could include a full web site with a page for postings, QC assistance, instrument information, etc.

3. What are the factors affecting the selection of communication technology?
4. How can needs be defined?
5. Will networks be linked through communication channels?
   It was decided that a spreadsheet is needed to assist a manager in the selection of a communication media to best suit AWN needs. The manager would first look at budget restraints, topography, demographics, and expertise available, then, using this spreadsheet, would determine which method of communications can be used for the specific network. The following spreadsheet was developed by Working Group B:

Mesonet Communications Grid

<table>
<thead>
<tr>
<th>Service availability</th>
<th>Phone Line</th>
<th>Short Haul</th>
<th>Cell Phone</th>
<th>GOES</th>
<th>Meteor Burst</th>
<th>Spread Spectrum</th>
<th>VHF</th>
<th>UHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skills needed</td>
<td>low</td>
<td>low</td>
<td>med</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Affected by land topo.</td>
<td>low</td>
<td>low</td>
<td>high</td>
<td>low</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Affected by vegetation</td>
<td>low</td>
<td>high</td>
<td>low</td>
<td>low</td>
<td>high</td>
<td>low/med</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Communication dist.</td>
<td>high</td>
<td>low</td>
<td>high</td>
<td>high</td>
<td>low</td>
<td>low</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>Base station</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes/no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Capitol cost</td>
<td>low</td>
<td>low</td>
<td>med</td>
<td>high</td>
<td>high</td>
<td>med</td>
<td>med</td>
<td>med</td>
</tr>
<tr>
<td>Operating cost</td>
<td>low</td>
<td>low</td>
<td>variable</td>
<td>variable</td>
<td>variable</td>
<td>low</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>Power</td>
<td>low</td>
<td>low</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Possible access rate</td>
<td>high</td>
<td>high</td>
<td>med</td>
<td>low</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>Data throughput</td>
<td>high</td>
<td>high</td>
<td>med</td>
<td>low</td>
<td>med</td>
<td>med</td>
<td>med</td>
<td>med</td>
</tr>
<tr>
<td>2-way communication</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Stable technology</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Affected by population</td>
<td>low</td>
<td>low</td>
<td>high</td>
<td>low</td>
<td>low</td>
<td>low</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>License required</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes/no</td>
</tr>
</tbody>
</table>
Working Group C
Sensors (Quality Control and Calibration)

Members: David Meek (CHAIR), Rick Ahlberg, Mark Crookston, Richard Grant, Gerritt Hoogenboom, Michael Layer, Dennis Lundy, Fred Nurnberger, Peter Palmer, Dennis Recla, Francesco Sabatini, Mark Silva, Maria Suarez, and Heikki Turtianinen

With regard to sensors, the following five questions were addressed by Working Group C.

1. Balance between quality, resources, and time?
   The primary purpose of the station must be clearly defined and the instruments chosen accordingly. Local constraints and circumstances must be identified so that the proper balance between quality needs, staff time, and other resources can be addressed.

2. Uniform calibration guidelines—handbook?
   The consensus was that knowledge of performance and calibration is plentiful for many of the common sensors. What may be useful in a new publication or guideline is a combination of a literature review and a directory that points to existing publications, like selected research papers and manufacturers’ manuals and publications. This work should be brief, something like a booklet. Organization by sensor type is the preferred format of most of the working group members. Although a hard copy is desirable, CD- and/or web-based versions are recommended. Also recommended is a list server for queries and problem solving on the subject.

3. Uniform QC guidelines—handbook?
   Recommendations on uniform QC guidelines parallel those in #2 above. We already know a lot about screening data. A more detailed summary follows this passage. Again, the recommended publication would be a guideline pointing to existing sources of information. Although a hard copy is desirable, CD- and/or web-based versions are also recommended. The list server recommended in #2 above could also be used for queries and problem solving on this subject.

QC/QA: We assume that proper siting exists and adequate maintenance and replacement occurs, including any QC/QA via advanced sensors that have self-checks like some sensors on the ASOS stations. Additionally, if possible, redundant instruments are recommended with appropriate analysis like cusum charts or internal software. The following recommendations apply only to data screening and employ most of the ideas offered in the workshop session dealing with QC. If no other information is available, then sensor limits can be used via automated data processing rules. If climatic data are available, then climatic-based LIM, ROC, and NOC rules should be developed and used to examine the time series record for each variable. For individual stations, appropriate comparison of related sensors is encouraged. For networks, paired comparisons and/or spatial maps and temporal surfaces of a variable should be examined along with some appropriate cross-comparisons of related variables. For some applications, specialized or expert analysis like sensitivity coefficients or gradient bounds can be employed. If it is not possible to carry out further tests on all of the data, we suggest, at a minimum, that the simpler rules be used to selectively inspect suspect data, which can then be subjected to further rule-based, graphical, or expert analysis.
Although most rules can, in the end, be coded and automated, some caution and visual examination of the record is prudent. Some possible considerations are:

—Many real events associated with natural phenomena may appear suspect based on the screening rules (e.g., a strong frontal passage, a localized event, a local geographic effect, etc.) and vice versa (recall the missing detection of the Antarctic ozone hole by the automatic processing of satellite data).

—Data good enough for one job may not be good enough for another. The automated rule base can and should evolve as the unusual or local phenomenon become well enough understood to be coded. For these reasons we argue that the final release of data should involve some human/graphical inspection of the data record. Moreover, the responsibilities of the provider and user should be clarified by policy before any data is released so there is no misunderstanding of either what or how reliable the data are. The job requires written policy, metadata, and careful documentation of the ongoing process.

4. Who to effect new publications—task force?
New publications on the types of sensors and their characteristics would be valuable to the growing population of AWS users. Organizations like the American Society of Agricultural Engineers (ASAE) and the World Meteorological Organization (WMO) could cooperate on such publications. The ASAE has ongoing work and experience with AWS stations and standards. It also has a history and an organizational structure that encourages cooperation with other institutions and societies It is suggested that workshop organizers contact relevant organizations on this matter to ascertain their interest in future publications.

5. What are the metadata requirements?
Given the time constraints, it was not possible to deal with metadata in depth. There is ample documentation addressing what is in a database, its variable definitions, period of averaging or summing, units, etc. The complete documentation of a site and transfer of any data needs to include this information. The commitment to developing and providing metadata is essential.

In summary, this working group offers three overall recommendations:

1. The assessment of the goals, sensors, and service/maintenance needs of an AWS station is primary. Commitment to station operation is essential.
2. Handbooks for calibration and QC guidelines are needed. They should contain literature reviews and indices of available information. CD and WEB versions are desirable.
3. List servers for each subject would be desirable.
Working Group D
Site Selection, Installation, and Maintenance

Members: Jen Winter (CHAIR), Jim Brown, Fernando Miranda, Nancy Selover, Ron Yeck, and Jose Vergara

A few of the questions considered by Working Group D were:

1. Is there a need for a bibliography on literature related to site selection?
   No bibliography dealing with “site selection” literature was known to Working Group D. A search of the literature would be helpful.

2. What are essential AWS site requirements?
   The cornerstone of site selection requirements is to determine the purpose of the data to be collected from the site. For example, if the data will be used in agricultural applications, then the site should represent an agricultural setting. Another major concern is site stability. Is permission to operate the site on the property affected by property ownership? Where is the site in relation to other AWS stations? Stations that are located in proximity may have too much redundancy. On the other hand, accuracy checking improves as the separation distance decreases. National and regional databases would help to avoid duplication. The database might include ownership, operational contacts, accessibility, geographical coordinates, and the sensors and data collection frequency. The WMO guidelines may serve as a good starting point for site requirements, and managers could alter or add requirements as needed to meet the specific project needs.

3. Can we define a standard format for describing a site?
   Do we need a standard format to describe the sites? This type of information is invaluable for anyone who may use the data in real time or in a historical sense. The site description might include aerial photographs, location plotted on a topographical map, photos corresponding to cardinal directions on the compass, descriptions of obstructions (height, distance, breadth), vegetation, and soil characterization. A site diagram would also be useful. Comments on land use surrounding the site or indications of land use from remote sensing data would also be useful.

4. Do we need a trouble-shooting manual?
   With regard to maintenance of sensors, it is recommended that AWS operators start with the manufacturers’ recommendations for maintenance and replacement of components, then make alterations based on the specific performance and accuracy observed during network operations. The prevailing climate (e.g., dry and dusty) may require more a more frequent maintenance schedule. Preventive maintenance is essential to overall network accuracy. The maintenance guide put together by Karl Blauvelt could be put on a Mesonets web site and expanded or modified to serve as a maintenance guide. Each network should have written procedures that document their maintenance policies. A trouble-shooting manual could also be developed in the same fashion, with modules included for each common sensor. A chat room or list server, and an archive for the list server with search capabilities, is recommended.
Working Group E
Future Direction of AWS Networks

Members: Mark Brusberg (CHAIR), Richard Heim, Gerritt Hoogenboom, Bart Nef, Ron Pitblado, Francesco Sabatini, M.V.K. Sivakumar, Barry Smith, Don Sytsma, Ken Stange, and Bert Tanner

Some of the questions considered by Working Group E were:

1. Should there be a network of networks?
2. How often should an AWS workshop be held?
3. What are the marketing, education, and outreach needs?
4. Who are the stakeholders and how can the linkages with users be enhanced to create strong support and a niche for AWS networks?
5. Would networks flourish if we developed business practices?

The following recommendations were brought forth:

1. Develop a national automated weather data archive center
   This center would serve as a repository for historical weather data from participating weather networks and protect all weather data from losses in case of network failure, etc. It was suggested that either a private-sector entity or a government agency operate the center. Interested parties should further discuss the placement and funding of the center and the tradeoffs that are involved with the decision.

2. Form a network operators user group
   A list server should be developed to support interactions between network managers and network technical support staff. This would offer a forum for technicians to exchange information regarding selection, calibration, etc.

3. Adopt methodology standards for new and existing network operations
   A good starting point for this is the 10 Climate Monitoring Principals (NCDC).

4. Schedule future AWS workshops/conferences
   Organizers of future AWS workshops should consider multiple sponsors (AMS, ASA, USDA, Department of Commerce, Department of the Interior, land grant schools, WMO). The meetings should be held in the United States every two years and internationally every four years. A steering committee could meet annually to update goals and objectives.

5. Establish linkages with users
   Linkages are needed to ensure future viability through support gained in new markets. Future work of AWS participants could include the identification of educational needs with respect to proper use of AWS in water resource and agricultural applications. AWS partners should follow the recommendations of the steering committee to ensure long-term sustainability and use new technologies like videos and CDs.
On the cover . . .

The future of society is tied to the demands for water from both agricultural and urban sectors. This photo shows one of the seven weather stations in Lincoln, Nebraska, USA, jointly sponsored by the Lincoln Wastewater System and the University of Nebraska.