Assessment of Texas Evapotranspiration (ET) Networks

Final Project Report

for completion of

TWDB Contract No. 0903580904

submitted to the

Texas Water Development Board
Austin, Texas

by

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Senior Research Engineer and Superintendent, NPRF
Texas AgriLife Research
Amarillo, Texas

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December 21, 2010

AREC 201011-12

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Lastly, we express sincere appreciation to our partners of the USDA-ARS Soil and Water Management Unit at Bushland, TX for their participation and continual support of ET and innovative water conservation based technologies that we cooperatively research to better serve the people of Texas, the nation and the world.

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Glossary of Terms and Abbreviations

A_C	Acreage of categorized crop denoted by c in a given county, acres
ac-in	acre-inch of water (volume of water equivalent to a 1 inch depth of water over the entire area of an acre of 43,156 square feet or ~27,154 gallons)
ac-ft	acre-foot of water (volume of water equivalent to a 1 foot depth of water over the entire area of an acre of 43,156 square feet or ~325,851 gallons)
AirT	air temperature
Cs	sensitivity coefficient
cm	centimeter
d	day
DewT	dew point temperature, sometimes referred to by dew temperature
^oF	temperature in degrees Fahrenheit
^oC	temperature in degrees Celsius
ER	Effective rainfall computed from seasonal rainfall occurring during the crop season, in.
ETc	crop evapotranspiration, mm/d or mm/h (in/d or in/h)
ETo	past term used to refer to reference evapotranspiration, mm/d or mm/h (in/d or in/h)
ETref	reference evapotranspiration, mm/d or mm/h (in/d or in/h)
ETrs	computed reference evapotranspiration using a tall reference (alfalfa) crop with a height of 0.50 meters with units of mm/d or mm/h (in/d or in/h)
ETos	computed reference evapotranspiration using a short reference (grass) crop with a height of 0.12 meters with units of mm/d or mm/h (in/d or in/h)
FSA	Farm Service Agency
h	hour
Hg	mercury
Hydromet	a network of automated hydrologic and meteorological monitoring stations and its collective associated communications and computer systems.
in	inches (1 inch = 25.4 mm)
in/d	inches per day

Glossary of Terms and Abbreviations (cont'd)

in/h	inches per hour
IRR_C	Irrigation applied on a seasonal basis to a crop, in.
IRR_{CTY}	Total quantity of irrigation volume applied (or pumped) to crops grown within a county in a given year or season, ac-ft
IRR_{REG}	Total quantity of irrigation volume applied (or pumped) to crops grown within a region in a given year or crop season, ac-ft
km^3	cubic kilometers (1 km^3= 810,713 acre-feet or ~264 billion gallons of water)
MJ	megajoules
mm	millimeters
mm/d	millimeters per day
mm/h	millimeters per hour
mph	miles per hour
m/s	meters per second
n	Number of categorized crops of interest per county
PET	potential evapotranspiration (an outdated, confusing and misleading term often used instead of the preferred term, ETref)
P_T	Grower factor which represents a fraction of the crop evapotranspiration pumped on a crop's seasonal basis and includes all irrigation systems and associated efficiencies (can be more or less than 1.0 reference crop ET, ETc
QA/QC	quality assurance/quality control
RH	relative humidity, %
Rs	solar radiation, watts/m^2
SQL	Structured Query Language
SR	solar radiation, watts/m^2 (This term is the commonly used for solar irradiance)
SRSM	solar radiation sensor model
SSM_D	Seasonal soil moisture depletion used in crop production which is extracted from the soil profile during the respective growing season, in.
WS	wind speed, m/s (mph)

Assessment of Texas Evapotranspiration (ET) Networks

Thomas Marek, Dana Porter, Prasanna Gowda,
Terry Howell and Jerry Moorhead[1]

Executive Summary

This project was conducted to ascertain the current status of evapotranspiration (ET) data and networks in Texas for potential and beneficial conservation use with irrigation decision support systems and in water planning efforts. The effort has particular application value as irrigation currently accounts for about 60 percent of the water use in Texas. In the Texas High Plains, irrigation accounts for nearly 90 percent of the entire water resource use. The project effectively addresses objectives that deal with the identification of current networks; the meteorological parameter data each network acquires, compiles and has available; the evaluation of meteorological parameter sensitivity on reference ET computation; the degradation analysis of available sensor base data and a comparison analysis of reference ET data from agriculturally based networks and non-ET data sources.

The results of this effort provide surprising and significant results in regards to several of the project tasks. First, the number of data sources discovered to exist within the state fell short of the number anticipated. Second, the number and scope of previously established agriculturally

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based ET networks in the state has declined with several more currently in jeopardy of ceasing operation. Third, there was found to be a surprising number of "miner" sites that poll and compile meteorological data within Texas that are located outside the region for a variety of reasons and applications. Fourth, there was found to be little to no adherence to any sensor or data standardization with a common QA/QC protocol among the various networks or data sources. Use of such data without qualification can directly lead to error prone computations, analysis and incorrect results. The sensitivity analysis task produced significant insight as to the required degree of sensor and parameter accuracy. Furthermore, inference as to the maintenance requirements of sensors on a routine basis became vitally clear from the computational analysis. While the sensor degradation analysis was limited to only one commercially available database, the results indicate a significant finding in that even new sensors often are faulty and can produce erroneous output signals and thus should be validated immediately after field installation. Comparisons of parameter data from differing network sources for potential use in reference (and agricultural) crop ET computations indicate that much manipulation is generally required, and documentation is typically insufficient in many cases to make the appropriate parameter adjustments. School-Net type networks were found to be of no value in representative agricultural based ET computations or applications.

Considering the effects of data accuracy, drift and sensor degradation utilizing the TAMA irrigation demand model in TWDB's designated Region A (see Figure 1), a seemingly small amount of incremental parameter data error results in staggering demand deviations on a regional basis in terms of increased irrigation demand or productivity losses. **Errors in ET calculation of 0.14 mm (or 0.0055 inch) per day would add up to a 1 inch increase in reference ET over a typical 183 day summer growing season. These small daily errors could be caused by a**

0.3 m/s (0.67 mph) wind speed error, a 0.6 degree C (1 degree F) temperature error, or a 14 watt per square meter (out of a typical maximum of 1100) solar radiation error or a combination of these sensor errors persistent over the growing period. When the 25 mm (1 in.) increase in reference ET is multiplied by the different respective crop coefficients and computed for all the current crop acreages within the region, the 25 mm (1 in.) reference ET error causes an increase in the 2010 Region A irrigation demand estimate of 52.68 million m^3 (42,707 ac-ft or 13.92 billion gallons). Extrapolating this additionally to Region O (located to the South of Region A), which uses twice the annual amount of irrigation water as Region A, the amount of water demand and importance of accurate ET becomes even more alarming. It should be apparent that this level of increased regional demand generally could not currently be met, particularly when considering the declining aquifer and existing pumping capacities in the Texas High Plains. Thus, ET requirements computed by inaccurate data should be unacceptable as Texas water resources must be accurately and appropriately utilized if the state is to manage and conserve the large amounts of water resources this analysis indicates are at stake.

The results of this project were disseminated in three seminar/workshop locations throughout the state of Texas. The first was held at the Texas Water Development Board headquarters in Austin in late July 2010 and presented to the Agricultural Water Conservation project leadership. The second was presented at the USDA-ARS Conservation and Production Laboratory at Bushland (located 12 miles west of Amarillo) in August 2010 and was attended by researchers and regional groundwater district personnel. The third was hosted in September by the Texas Water Resources Institute on the campus of Texas A&M University in College Station and was well attended by state ET network personnel, graduate students, Spatial Sciences Laboratory personnel and a TWDB project representative.

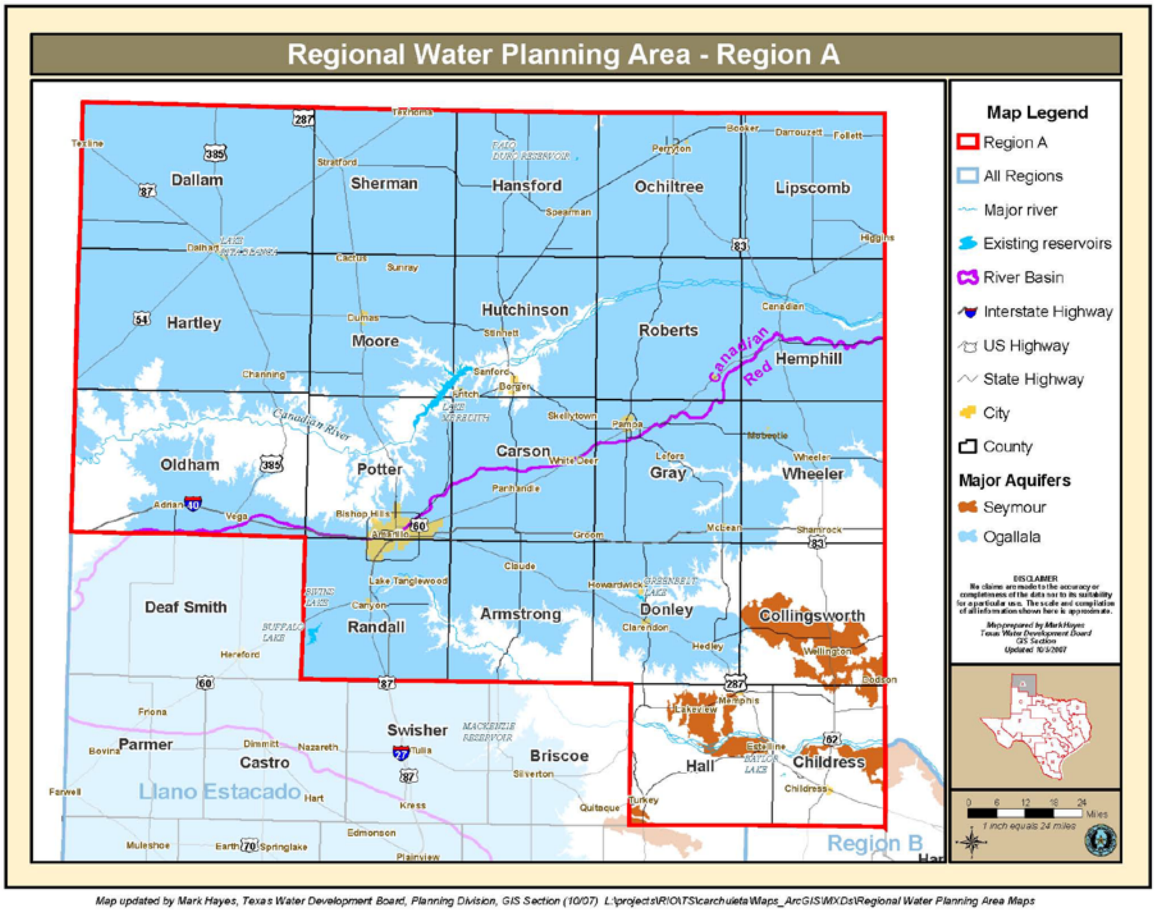


Figure 1. Map of TWDB RWP Region A - Texas Panhandle. (Source: TWDB, 2010).

There are several recommendations that result from this effort. Given the diversity and vastness of Texas and considering the significance of these somewhat alarming findings and the amount of state water resources that the deviations potentially impact, a sustainable mechanism for funding agriculturally based ET networks or alternate acceptable data sources is warranted on a continuing basis. Seeking sustainable funding resources continues to be a recurring challenge for existing ET networks and several are pending shutdown, particularly with agencies facing state budget shortfalls and selecting different priorities. A mechanism or contract for data with network support needs to be developed and agreed upon by the participating members and the TWDB, as the state's water agency, should possibly consider possession of the funding and coordination responsibilities. Additionally, a statewide database of acceptable, documented and maintained data and sources should be electronically warehoused and made readily available for use in research, education and water planning. To not adequately address and support these recommendations may ultimately risk the water resources future and the crop production potential of Texas.

Introduction and Background

In Chapter 10 under Agricultural Water Conservation of the 2007 Texas state water plan (TWDB, 2008), it is stated that irrigated agriculture statewide is the greatest water consumer using about 60 percent of all water demand. In Regions A and O (the Texas High Plains regions), irrigated agriculture comprises approximately 90% of total water demand (Marek et al., 2004 and Amosson et al., 2003). Twelve of the 16 Texas regional plans include irrigation water use management as one of their top water conservation priorities. Irrigation scheduling is the first conservation management strategy listed, and this project addresses current infrastructure and information necessary for successful implementation of the irrigation scheduling strategy through the use of accurate meteorological data and representative calculations.

Evapotranspiration (ET) is defined as a measure of the total water demand through evaporation from soil (and other surfaces) and plant transpiration to the atmosphere. Crop ET (ETc) is a measure relating to ET demand specific to a particular crop being grown at the soil surface. **"***Potential evapotranspiration (PET) is a representation of the environmental demand for evapotranspiration and represents the evapotranspiration rate of a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile. It is a reflection of the energy available to evaporate water, and of the wind available to transport the water vapour from the ground up into the lower atmosphere. Evapotranspiration is said to equal potential evapotranspiration when there is ample water.*" (Wikipedia, 2008). The typical short green crop is a "reference" crop that is either alfalfa or a grass, with both being well watered. Grass is generally the preferred reference crop in arid and semi-arid areas. Thus, reference ET (ETref and previously designated by ETo) – rather than PET - is the preferred term describing potential water demand with the reference crop being specified.

Several methods of estimating crop ET have been developed over the years and estimations have been published using differing methods based on available data. The Texas Board of Water Engineers published a monthly estimation of crop ET for differing parts of the state (TBWE, 1960) but these data were average based data and did not reflect any seasonal variations of weather. Others such as Borrelli et al. (1998) provided an updated version of similar data but still based on average conditions.

Reference ET (ETref) can be accurately computed from meteorological data recorded from weather stations that are instrumented with properly calibrated sensors and programmed for hourly (or shorter interval) data acquisition output. Crop-specific water use by growth stage derived from lysimeter studies can be used to develop crop coefficient curves to relate reference ET to crop specific ET (ETc) that can be used in daily irrigation scheduling programs, water demand models and other applications (Marek et al., 2010). The accuracy of these ETc values is highly dependent on characterization parameters such as site location and representation - particularly in regards to topography, wind obstructions, buildings, soil surfaces, roadways, hills, valleys, draws, drainage and waterways, lakes and ponds, playas and cover crop influences among other impacting factors.

Using the same weather station output data, various methods of ET computation can result in differing ET values. This situation created cause for researchers and irrigation industry personnel. To standardize ET computation and improve the application, comparison and transferability of ET research and crop coefficients, the ASCE Standardized Reference Evapotranspiration Equation (Allen et al., 2005) was established by a national team of ET scientists and engineers located throughout the U.S. whereby comparative computations could be made irrespective of climate area and reference crop used. The effort was requested by scientific and educational communities and the Irrigation Association, who were particularly concerned about the differences in ET estimates derived from the same data parameters but with different ET calculation methods. Currently it is not known how all of the respective weather networks in Texas compute ET. Furthermore, clientele have reported confusion about which computed ET value to use in irrigation scheduling software and related tools. This confusion can and has hindered adoption of ET-based irrigation scheduling in Texas and elsewhere. Since irrigation scheduling has been identified as one the priority water conservation strategies in many of the state's regional water plans and the statewide plan, there is a statewide need to identify and document parameters associated with the current ET networks and to assess the need for uniform methods of computation and standardized data parameters.

Project Objectives

This evapotranspiration (ET) network assessment project entailed a thorough assessment and review of ET networks throughout the state of Texas, as requested and awarded per the Texas Water Development Board (TWDB) RFA in 2008. The following objectives were addressed with this investigative effort to document, advocate and potentially implement an improved and more uniform irrigation scheduling basis within Texas:

1) Identify and review the existing ET and other selected weather station networks to assess functionality and applicability to ET-based irrigation scheduling,
2) Visit with network managers and review operations, data collection and quality assurance/quality control (QA/QC) procedures, methods of ET computation of networks throughout Texas,
3) Conduct sensitivity analyses to determine the degree of accuracy of data parameters and sensors necessary to achieve acceptably accurate ET estimates,

4) Analyze commercially available weather station sensor degradation database(s) to determine the effects of sensor degradation (over time) on quality of data recorded by ET networks,
5) Compile and compare parameter data of existing ET networks and assess their suitability for irrigation scheduling applications, and
6) Communicate project results and provide recommendations regarding identified areas, instrumentation and methods of computation.

Tasks and Approach

Identification, visitation and review of sensors and computational methods in discussion with existing ET network personnel were to be conducted throughout the state. This information was to be compiled into a matrix whereby comparative uniformity could be assessed. Concurrently, an analysis of the sensitivity of weather station parameters was to be conducted to determine the degree of sensor accuracy necessary to achieve acceptable ET estimate results. A sensor degradation analysis from commercial recalibration database(s) also was to be conducted for assessment of data drift. Finally, recommendations regarding deficiencies or upgrades/improvements needed within the existing networks were to be determined and reported.

Task 1: ET network identification.

There are numerous weather station networks and data sources located in Texas. Several of these include local and regional networks that provide evapotranspiration (ET) information to support irrigation management and other water conservation/water management activities. Through this task, the team was to identify and review networks to assess functionality and applicability for providing irrigation scheduling support.

Task 2: Site visitations, review discussions, acquisition parameters and QA/QC procedures.

Through performance of this task, the project team was to survey and visit a significant number of networks statewide, and conduct a review of their respective network sensors, data collection and processing, operations, dissemination venues, costs and computational methods used in estimating ET. This information was to be compiled for an assessment of uniformity and applicability analysis. This task was to require extensive travel to visit the multiple locations throughout the state and to meet with the respective network managers/operators of the networks.

Task 3: Sensitivity analysis of network based parameter data.

High levels of accuracy and quality of data are desired and expected from ET networks. Realistically, however, some data inaccuracy due to weather station placement, sensor calibration drift and other factors is inevitable. A sensitivity analysis was to be conducted to determine the degree of sensor accuracy necessary to achieve acceptable ET estimate results. This effort was to include analytical interpretation by the research team, as well as data analysis and processing. Specifically, the analysis was to include delineation of ET input parameters singularly for assessment of sensitivity to ET computational impact. This effort was to be conducted for a representative set of agriculturally based ET data, envisioned using Bushland input data sets with the results data summed for the crop season and compiled through the Texas A&M-Amarillo (TAMA) irrigation water use model for regional impact on irrigation water demand.

Task 4: Weather station sensor degradation analysis.

Many agricultural weather stations in the field fail to meet all the recommended sensor performance and maintenance criteria for accurate and representative ET computations. Remote placement of many stations, station exposure to harsh environmental conditions and shortage or lack of experienced field personnel and funding to adequately maintain the equipment contribute to the deterioration of sensors with time. This weather station sensor degradation analysis was to evaluate the temporal degradation of sensors and the relative effects on quality of data reported by evapotranspiration networks.

This task was to involve evaluation of long term, commercially compiled database(s), hence the scope was dependent upon availability and content of the database(s). Evaluation of sensor degradation over time and assessment of the relative effects on the computation of ET was to be used to develop recommendations related to the recommended interval of replacement/recalibration for the respective sensors in differing environments, where possible. This analysis was also to provide updated and in some cases unique data regarding the degradation of sensor data, if determined, from agriculturally based ET stations which was to be subsequently considered for integration into the national ASABE EP505 Standard (currently under revision) that may be used as a guide for current and future ET weather station installations in Texas and within the agricultural areas of the nation.

Task 5: Compilation and comparison of parameter data and application suitability.

This task was to entail compiling and tabulating the results of Task 2. A comparative analysis using Task 3 results on the data of Task 2 was to be evaluated for adequate representation and accuracy. Additionally, recommended network standards for proposed ET networks were to be determined based upon the data analysis. Some ET networks were established for the primary purpose of providing ET based irrigation scheduling information. Other weather monitoring networks may include ET information as a secondary function, or their data may be used by third parties for ET estimation. Under this task, network data were to be compiled and compared to assess suitability of these non-agricultural designated datasets for ET based irrigation scheduling and water planning purposes.

Task 6: Interpretation of results, report preparation, printing, submission, and educational meetings for targeted audiences.

Results from Tasks 1 through 5 were to be reported and interpreted in the context of practical considerations for ET network management and data quality. Sensor based analysis and subsequent recommendations were to be developed to help weather networks address deficiencies, if and where identified. Three to four targeted educational meetings were to subsequently be conducted throughout the state to provide information to the TWDB agency personnel, ET network managers and other interested ET network personnel regarding the study results. These locations were determined and mutually agreed upon by the TWDB and the project research team.

Task 1

ET Network Identification

Methodology

Weather information is abundant throughout the World Wide Web. Many websites display current conditions or future forecasts. Many weather information websites make it easy to display their information on their respective and individual websites. The accuracy and quality assurance/quality control (QA/QC) protocols implemented regarding current and past data, however, are much more difficult to find. There are some data sites that provide past data that can be valuable for research and agricultural purposes. The status of methods used to collect these data and the degree of adequate QA/QC were not well known on a state basis prior to this project.

The method of approach used to identify weather station networks was primarily through internet searches to find any and all networks that would provide the desired meteorological parameter data. Once a network was found, a thorough navigation of the website was conducted to find any links to additional data sources as well as identify the information available from the respective network or site. The information sought from each network included parameters collected, data transmission method, weather station location and setup, sensor type and models, power requirements, measurement interval, output interval, QA/QC methods, contact information, measurement units, number of stations, measurement resolution, current status of the data and whether the data were downloadable. These parameters were important to determine if the data source network was viable for ET calculation. Knowledge of the sampling interval would allow determination as to whether the hourly and daily outputs were averages over a period of time or if they were one time (sampled) measurements taken at a specific time.

Averaged values tend to be more representative than a single measurement due to the fact that a single measurement can be taken at a high or low point, which may not accurately reflect the integrated weather for the hour, day or interval of interest. The output interval allows one to know if ET can be calculated on an hourly or daily basis (and possibly even for shorter periods). Hourly ET values can be summed to provide a daily ET value that is more accurate than a calculated ET value based on averaged daily weather data. The interest in weather station location and setup, data transmission mode and power requirements was to determine limitations to the networks' site selection as well as to know what the common components are for the networks throughout the state. Knowing which models of sensors were used would allow assessment of differences in measurements due to sensors. Also, knowledge of sensor types would allow the determination of similarities or differences within the various networks. It was anticipated that the QA/QC procedures would differ significantly based on each network's design and purpose. Finding contact information and pursuing follow-up discussion with personnel from each network would allow the acquisition of more information regarding any details about the network as well as visiting and documenting the network weather stations. Knowing the units of measurement would allow comparison of data for each parameter in the same units. Investigation as to the number of stations for each network would yield network coverage within the state. Knowing where each network located weather stations could also assist in determining which networks were available for selected comparison of data values (with respect to one of this project's tasks). Knowing the resolution of the respective sensor measurements would allow assessment of what degree of accuracy could be obtained from the data. Higher resolution data generally lead to more accurate calculations due to less rounding of the parameter values before computation. Display resolution is often different from the recorded or archived data resolution. There was also interest in knowing how recent the available data were and if they could be downloaded. If recent (near real-time, within days) data cannot be obtained, then viability for current ET calculations diminishes accordingly. For instance, there is not much value in month old computed ET data for in-season irrigation scheduling. In addition, if data are not available for download, it makes viable use of that network difficult. All possible relevant information was gathered for each network to fulfill the goals of task 1 in addition to assisting with the other tasks.

Through this research, all relevant weather networks that can be used for ET calculation as well as several networks that provide some, but not all weather data parameters needed for computation of ETref were identified. Networks that were not viable for ET use were still researched and included in this report to provide a thorough assessment of available weather data for the state. The reasons these sites were developed vary considerably and warrant merit and potential usefulness beyond the purpose of this investigation. Some useful purposes include climatology research, preparation for severe events, water source monitoring for pollution or quantity, air pollution monitoring, weather forecasting and severe weather warning.

Agricultural meteorological (AgMet) networks differ from most weather station networks in that their primary purpose is the collection of data for use in agricultural applications. Most of these networks take all the necessary measurements for calculation of ETref in addition to other parameters that assist with agricultural processes. For example, soil temperature data are useful in determining appropriate planting dates following the winter season. Many weather websites are designed for reporting current conditions and for forecasting purposes. Many sites display a wealth of information but do not make the information available in a storable format. In addition, the quality of the data is a major concern regarding agricultural weather. Generally, low quality data yield low quality results in calculations or estimations. Seemingly small discrepancies in data can have profound effects with regard to water consumption in the agriculture sector because the multipliers (typically acreages) on an agricultural scale basis are large, particularly in the Texas High Plains.

Network suitability for ET calculations is determined by the parameters measured by each network. For ET calculations, the minimum parameter requirements include air temperature, wind speed, relative humidity and solar radiation. These are the four essential meteorological inputs used in the ASCE ET formula. Some of the networks identified collect these four parameters, while others record only air temperature, wind speed and relative humidity. Although some networks do not record solar radiation, this parameter can be estimated. This capability makes those networks without this parameter potentially useful for ET calculation. However, it should be noted that estimated solar radiation values will contain some degree of inaccuracy. (The sensitivity of ET estimates to solar radiation data accuracy is evaluated in Task 3).

Results

The weather networks identified in this project that provide the four necessary parameters for ET calculation include the Texas High Plains ET Network, the Texas ET Network, the West Texas Mesonet, the Crop Weather Program, MesoWest, the Real-time Observation Monitor and Analysis Network, the Desert Research Institute, the Texas AgriLife Center at Beaumont iAIMS, the Weather Underground, the Texas AgriLife Center at Overton and the New Mexico State University Climate Center. The ET networks that use the ASCE standardized method of reference ET computation are the Texas High Plains ET Network and the Texas ET Network, which are the two largest networks in Texas. Other networks that measure temperature, wind speed and humidity include the Iowa Environmental Mesonet, KVII School Net, the National Weather Service, the National Climatic Data Center, the Midsouth Weather Network and the KVIA Weathernet Lab. These data sources do not include solar radiation, which is a necessary component of ET calculation, but as mentioned previously solar radiation values can be estimated. Other networks and data sources included in this report that are not viable for ET calculation include the USDA Weekly Weather and Crop Bulletin, the U.S. Historical Climatology Network, the Lower Colorado River Authority, the Community Collaborative Rain, Hail and Snow Network, the Texas Coastal Ocean Observation Network, the Texas Commission on Environmental Quality, the Bureau of Reclamation and WeatherBug.

Texas High Plains Evapotranspiration Network

The Texas High Plains Evapotranspiration (TXHPET) Network is a system of nineteen weather stations throughout the High Plains region of Texas. This network is operated through the Texas AgriLife Research and Extension Centers at Amarillo and Lubbock. It is a true collaboration between the North Plains Evapotranspiration Network and South Plains Evapotranspiration Network. These weather stations measure soil temperature at two inches and six inches, air temperature, dew point temperature, relative humidity, saturation vapor pressure, actual vapor pressure, vapor pressure deficit, solar irradiance, wind speed, wind direction, precipitation, leaf wetness and barometric pressure. Measurements are taken in International Standard units of: watts per square meter for solar irradiance, Celsius for temperatures, percent for relative humidity, kilopascals for pressure, meters per second for wind speed, degrees for wind direction and millimeters for precipitation. Computed ET is also in mm. The data from these stations are used in evapotranspiration calculations and made available to the public via the internet (see figure 2).

The Texas High Plains Evapotranspiration Network website provides information detailing evapotranspiration and how it can be used in agricultural applications along with the weather data. The measurements are taken at six second intervals and stored in internal memory at the weather station site. Generally, the data are collected remotely on a daily basis using a PC computer utilizing a modem and a standard phone line connection at each station. Some sites utilize a cellular modem and IP based setup for data interrogations. Data are compiled and ET computations made daily after midnight for the previous day. Comparative QA/QC operations on the data are performed weekly. The data can be viewed online in graph or data table format. Daily and hourly values are available for download as text files or in an ASCII, comma delimited format. Although the measurements are taken in metric units, these data can be displayed in English units. The TXHPET network also operates a listserv that delivers daily email files containing the weather data. Weather data are available from the date the station went online to yesterday's date. Users of the website can select daily or hourly data, which weather stations to display, the time range of interest, parameters and units and the output format. Users can also select to view the hourly printout, which displays the hourly readings for the selected site with daily cumulative or mean values. In addition, links from the website allow convenient access to daily soil temperatures at two inch and six inch depths for the current calendar year. The fax format files sent to the listserv for yesterday's data can be viewed by using a simple link. This fax format was derived and solicited from producers' preferences whereby a single page contained the condensed yet diverse crop and ET information which could be readily used. Another link can be used to access the 1, 3 and 7 day ET water use of fescue, bermuda and buffalo grasses. These data are principally for use in the urban environment, and the three grass varieties represent low, medium and high water use grass categories, respectively.

The TXHPET network was designed for irrigation management to be used in the most intensively irrigated region in the state. The purpose of this network is to provide timely, accurate meteorological data for use in agricultural irrigation management and other associated agricultural applications. The network has been funded in part by Texas AgriLife, the USDA-ARS and by intermittent grant support of commodities and groundwater conservation districts over time.

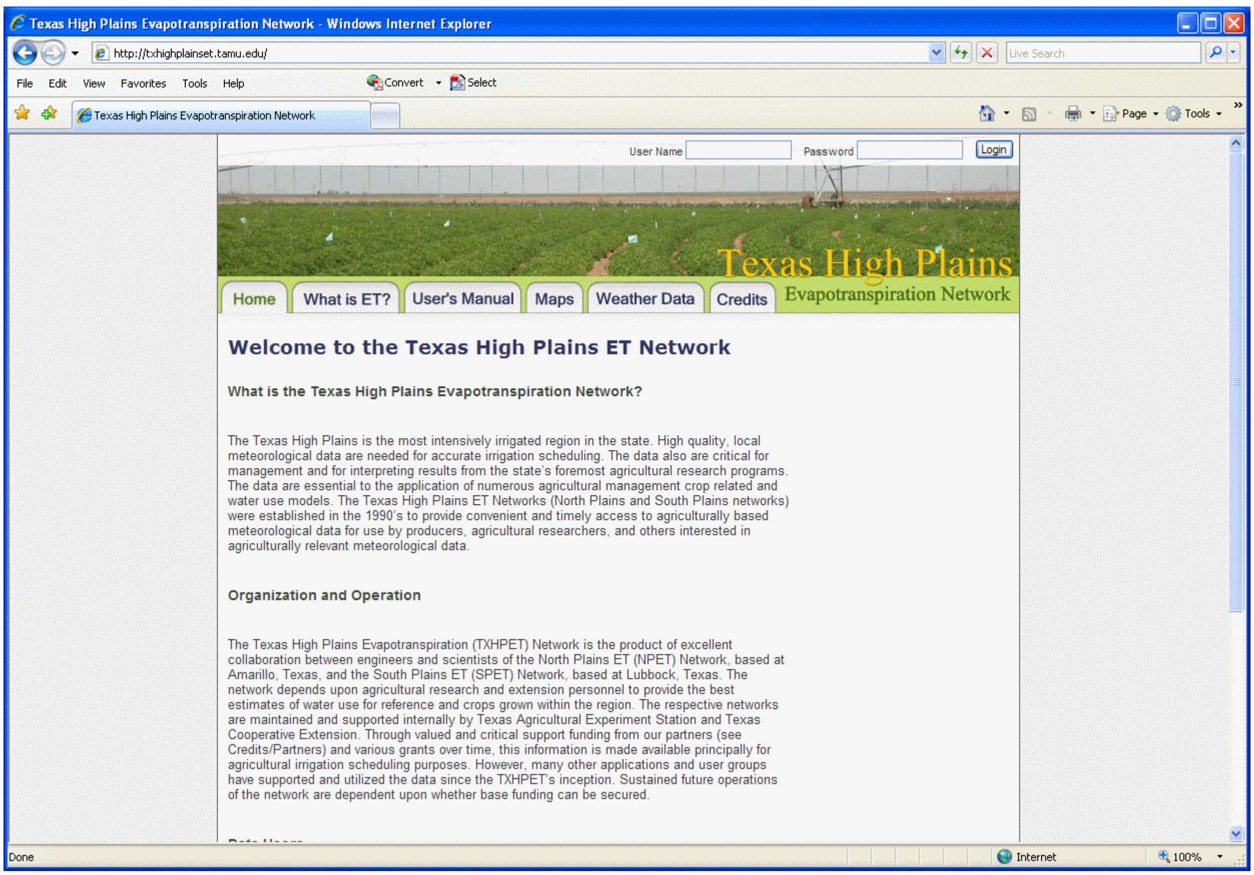


Figure 2. Texas High Plains ET Network website front-page. (Source: TXHPET, 2010).

Development has been made possible through numerous grants including those from the Texas Water Development Board. The TXHPET network collects or stores data from stations located at Bushland-ARS (Agricultural Research Service), Bushland-JBF (James Bush Research Farm), Chillicothe, Dalhart, Dimmitt, Earth, Etter, Farwell, Halfway, Lamesa, Lockney, Lubbock, Morse, Munday, Pecos, Perryton, West Texas A&M (WT) Feedlot, Wellington and White Deer. The sites at Bushland-ARS, Bushland-JBF, Chillicothe, Etter, Halfway, Lamesa, Lockney, Lubbock, Pecos, and the WT Feedlot are located at agricultural research locations. Of these stations, Munday and Earth are offline and contain historical data only. A station is scheduled to become active near Vernon (Lockett) in the future to support Texas AgriLife research and extension programs.

As of September 1, 2010, the TXHPET network has exhausted financial resources for operations and maintenance. Limited grant funds are currently supporting selected research projects at a reduced level of service. After December 31, 2010, many TXHPET network stations will be fully decommissioned and only project specific research site stations are planned in the future.

West Texas Mesonet

West Texas Mesonet (WTM) is a network of 56 weather stations located throughout west Texas with two stations in eastern New Mexico. This project is operated in collaboration with Texas Tech University. This network was established to provide real-time weather data for operational meteorology, agriculture and farming, research and media purposes. These stations record readings of wind speed and direction at a ten meter (33 ft) height, temperature at a nine meter (29.5 ft) height, wind speed at a two meter (6.6 ft) height, temperature at a two meter (6.6 ft) height, temperature and relative humidity at a 1.5 meter (4.9 ft) height, barometric pressure, rainfall and solar radiation at a two meter (6.6 ft) height. These measurements are recorded at five minute intervals. At 15 minute intervals, the stations measure soil temperature at the depths of 5, 10 and 20 cm (2, 4 and 8 in. respectively) under sod covered ground, soil temperature at depths of 5 and 20 cm (2 and 8 in.) under bare ground, soil moisture at depths of 5, 20, 60 and 75 cm (2, 8, 24 and 30 in.) with sod covered ground and leaf wetness. The WTM measurements are displayed in units of: Fahrenheit for temperatures, miles per hour for wind speed, degrees for wind direction, inches for precipitation and watts per square meter for solar radiation.

The WTM website (see figure 3) provides potential ET for each weather station as well as soil water content at varying depths. One link shows the current observations for all weather stations. Selecting one station shows the five minute readings for that station on the current day. Users can access the daily summary archive and enter a date to display five minute readings for that day for a selected site. The bottom of the daily summary shows the maximum and minimum values for each measurement for that day and time of occurrence. This information can be saved as a text file. The website also has a clickable map feature to view current weather observations. A map is displayed with the location of each station marked. The user can click one of the locations to see the observations in a display pane. Another link will lead the user to a soil conditions page. This page shows the time of the last measurement, grass covered soil temperature at 5, 10 and 20 cm (2, 4 and 8 in.) depths, as well as bare soil temperature at 5, 10 and 20 cm (2, 4 and 8 in.) depths. This page also gives the soil water content at 5, 20, 60 and 75 cm (2, 8, 24 and 30 in.) depths. The soil water content cells of the spreadsheet are highlighted in different colors that correspond to different levels of moisture. This gives the user a visual representation of the moisture content. There is also a clickable map for soil data. The map is similar to the current conditions map, and gives the maximum, minimum and current soil temperatures of naturally covered and bare soil. In addition to temperature, this clickable map feature displays leaf wetness, maximum leaf wetness and soil moisture content at 5, 20, 60 and 75 cm (2, 8, 24 and 30 in.) depths. There is another page that shows climate and evaporation data, including the time of the last measurement, maximum and minimum air temperature, maximum and minimum dew point temperature, maximum and minimum relative humidity, prevailing wind direction and daily average wind speed at the 10 meter (33 ft) height, average wind speed at the 2 meter (6.6 ft) height, peak gust at the 10 meter (33 ft) height, potential evapotranspiration in millimeters per day and inches per day, total rainfall, accumulated solar radiation and percent clear day solar radiation.

Figure 3. West Texas Mesonet website front-page. (Source: WTM, 2010).

WTM data are obtained from the stations using extended line of sight radio, cell phone, landline phone, DSL or cable modem, wireless internet and spread spectrum radio transmission to available internet. The WTM has stations in Texas located in or near Abernathy, Amherst, Andrews, Anton, Aspermont, Brownfield, Childress, Clarendon, Denver City, Dimmitt, Floydada, Fluvanna, Friona, Gail, Goodlett, Graham, Guthrie, Hart, Haskell, Hereford, Jayton, Knox City, Lake Alan Henry, Lamesa, Levelland, Lubbock, McLean, Memphis, Muleshoe, Morton, Northfield, ODonnell, Olton, Paducah, Pampa, Plains, Plainview, Post, Ralls, Reese Center, Roaring Springs, San Angelo, Seagraves, Seminole, Seymour, Silverton, Slaton, Snyder, Spur, St. Lawrence, Sundown, Tahoka, Tulia, Turkey, White River Lake, Wall and Wolfforth. The WTM also has two New Mexico stations located at Dora and Tatum.

Crop Weather Program

The Crop Weather Program (CWP) is a network of weather stations operated through the Texas AgriLife Research and Extension Center at Corpus Christi. This network consists of nineteen stations along the Texas coastal plains. The CWP has stations located in the following counties: two in Bee, Calhoun, Fort Bend, Glasscock, Jackson, Kleberg, Matagorda, four in Nueces, two in Refugio, four in San Patricio, Uvalde, Victoria, Wharton and Williamson. These stations measure environmental data that affect crop growth. The Crop Weather Program (see figure 4) provides tools for PET reference, pre-plant soil temperature, post-plant soil temperature, soil moisture, crop water use, crop development, crop defoliation and irrigation monitoring. The CWP allows access to hourly and daily data. The daily data range is from 1994 to present, and the hourly range is from 1996 to present. A user must register to gain access to the CWP data. Once logged in, the user selects a site from which to view data. The measurements taken include maximum temperature, minimum temperature, average temperature, relative humidity, solar radiation, wind speed, wind direction, soil temperature at the 2.5, 7.6 and 20.3 cm (1, 3 and 8 in.) depths and precipitation. The units of the measurements are degrees Fahrenheit for temperature, percent for relative humidity, calories per square centimeter per day for solar radiation, miles per hour for wind speed and inches for rainfall. CWP data are collected by the stations and transmitted over land lines and wireless networks by an automated acquisition system. Users can select a data range of up to 720 hours for hourly data and 366 days for daily data. The selected data can be downloaded as a comma delimited text file. In addition to weather data, the CWP site has tools to calculate reference ET and soil moisture, among other tools. This website allows users to create a field profile, which allows the use of the closest weather station to the field for more accurate calculations.

Figure 4. Crop Weather Program website front-page. (Source: CWP, 2010).

Texas ET Network

The Texas ET (TXET) Network is a network of weather stations located throughout south and central Texas. It is project of the Irrigation Technology Center, a center of the Texas Water Resources Institute in the Agriculture Program of the Texas A&M University System. Texas ET is a service network provided under the direction of Dr. Guy Fipps, Extension Irrigation Specialist, Texas AgriLife Extension Service and Department of Biological and Agricultural Engineering, Texas A&M University. This network currently operates thirty-five stations throughout Texas that measure air temperature, relative humidity, solar radiation, precipitation and wind speed. The units in which the measurements are taken can vary depending on the weather station. The data are displayed in units of inches for ET, Fahrenheit for temperatures, percent for relative humidity, megajoules per square meter for solar radiation, inches for rain and

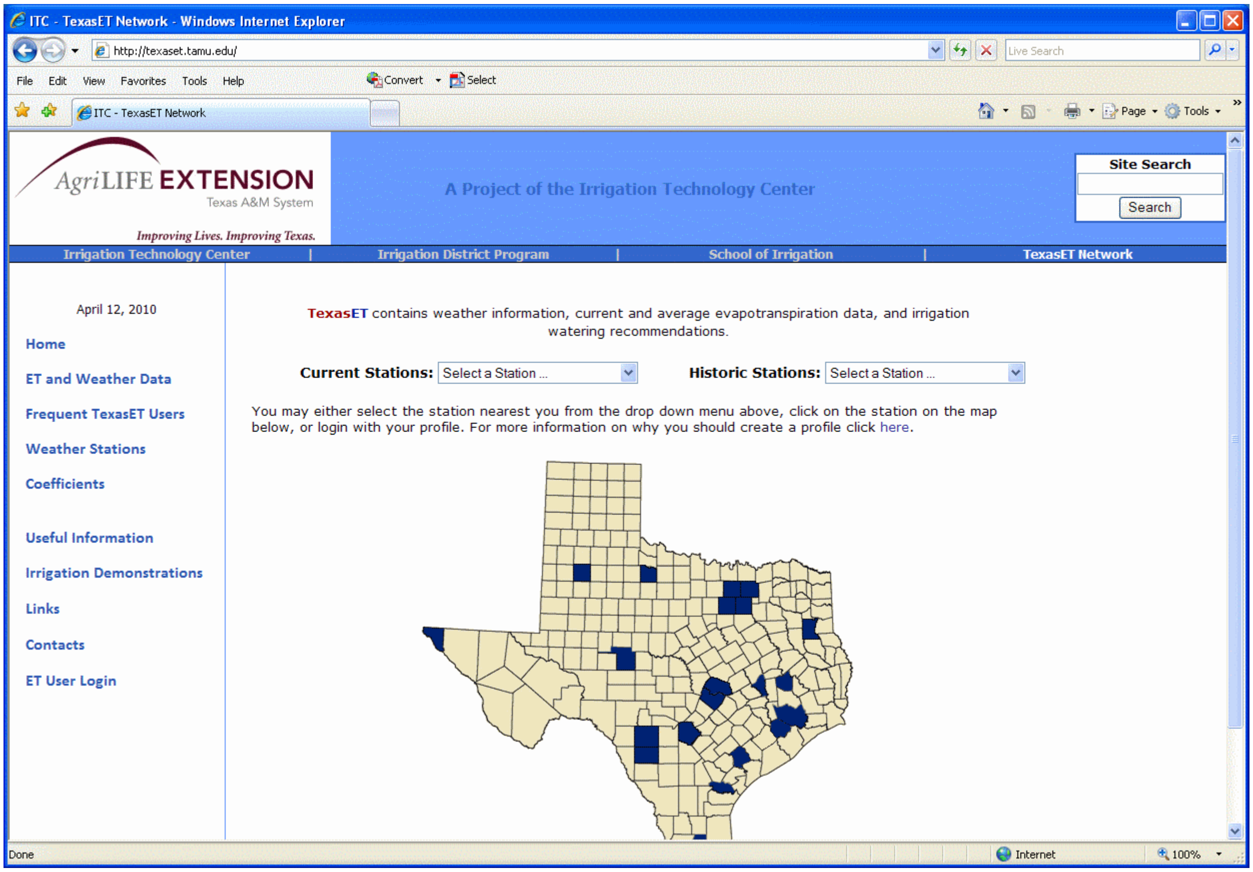


Figure 5. Texas ET Network website front-page. (Source: TXET, 2010).

miles per hour for wind speed. The Texas ET Network records data from stations located in Irving, Dallas, Frisco, Lubbock, Seymour, Overton, four around El Paso, Georgetown, two in Austin, College Station, Huntsville, Kingwood, Fort Bend, Concan, Sabinal, Knippa, Uvalde, La Pryor, Frio Town, Crystal City, Carrizo Springs, two in San Antonio, Victoria, Sinton, Tres Corles, three around Weslaco and Mission (United Irrigation District). Archived data from some stations that are no longer online are also available. The user can select a data range of a number of days or select specified dates. A summary of the selected range is displayed at the bottom of the web page. Current data are available for most stations. The website (see figure 5) displays ETo, maximum and minimum air temperatures and wind speed at 4am and 4pm in the daily summary. Archived hourly data as well as the daily summaries can be downloaded as a text file for the time period of interest. The TXET site contains a webpage that shows the status of each of the weather stations. This allows the user to assess if the data have been recently acquired from the station of interest. The site has links to historic average values of ETo, rainfall, air temperature and relative humidity. Averages are provided on time scales of a month and include the average sums per year, where applicable.

The Texas ET Network website includes links to background information to assist users in applying the ET information. It also provides useful tools for home watering, turf/landscaping irrigation and crop irrigation. The home watering tool allows user input of sunlight exposure, turf type and effective rainfall, and it will output the water requirement for that specific lawn. User-input precipitation rate is used to recommend total run time for the irrigation system, the number of irrigations per week and the run time per irrigation. The turf/landscape tool imports the ETo value from the weather data and asks the user to input the plant or grass coefficient from drop down menus with options for cool or warm season turf along with frequently watered, occasionally watered, or natural rainfall watered plants and appropriate adjustment factors. The crop irrigation tool imports the ETo value from the weather data, incorporates user-selected crop and growth stage information to select an appropriate crop coefficient, and takes into account effective rainfall and irrigation system efficiency and precipitation rate information to calculate the recommended total run time, the number of irrigations per week and run time per irrigation event.

MesoWest

MesoWest is a collaboration between the National Weather Service (NWS) and researchers at the University of Utah. This website observes NWS, remote automated weather stations (RAWS), Federal Aviation Administration (FAA) and other stations. This project provides weather data for the western United States. Observations from almost 1,200 weather stations are acquired throughout the state of Texas. These weather stations measure air and dew point temperatures, wet bulb temperature, relative humidity, wind speed and wind gust. Measurements are taken in five minute intervals and can be displayed in either English or Metric units. This network (see figure 6) offers a map of weather stations showing the most recent observations. The parameters displayed can be changed to show desired parameters. The wind speed and direction are shown for each station by a wind barb. In addition to the wind barb, up to two other measurements can be selected for display. The map can be changed to show data for a selected date. Each station is indicated by a black dot, which displays a box with the current wind speed and direction, air and dew point temperature and relative humidity as well as the date and time of the last observation and elevation.

The MesoWest weather data listed include current conditions of air and dew point temperature, relative humidity, wind speed and direction and peak gust. Also included are the 24 hour maximum and minimum values for air and dew point temperature, relative humidity and maximum wind gust. Below the listed data is a graph plotting air and dew point temperature and relative humidity for the past 24 hours. The graph can be changed to view wet bulb and dry bulb

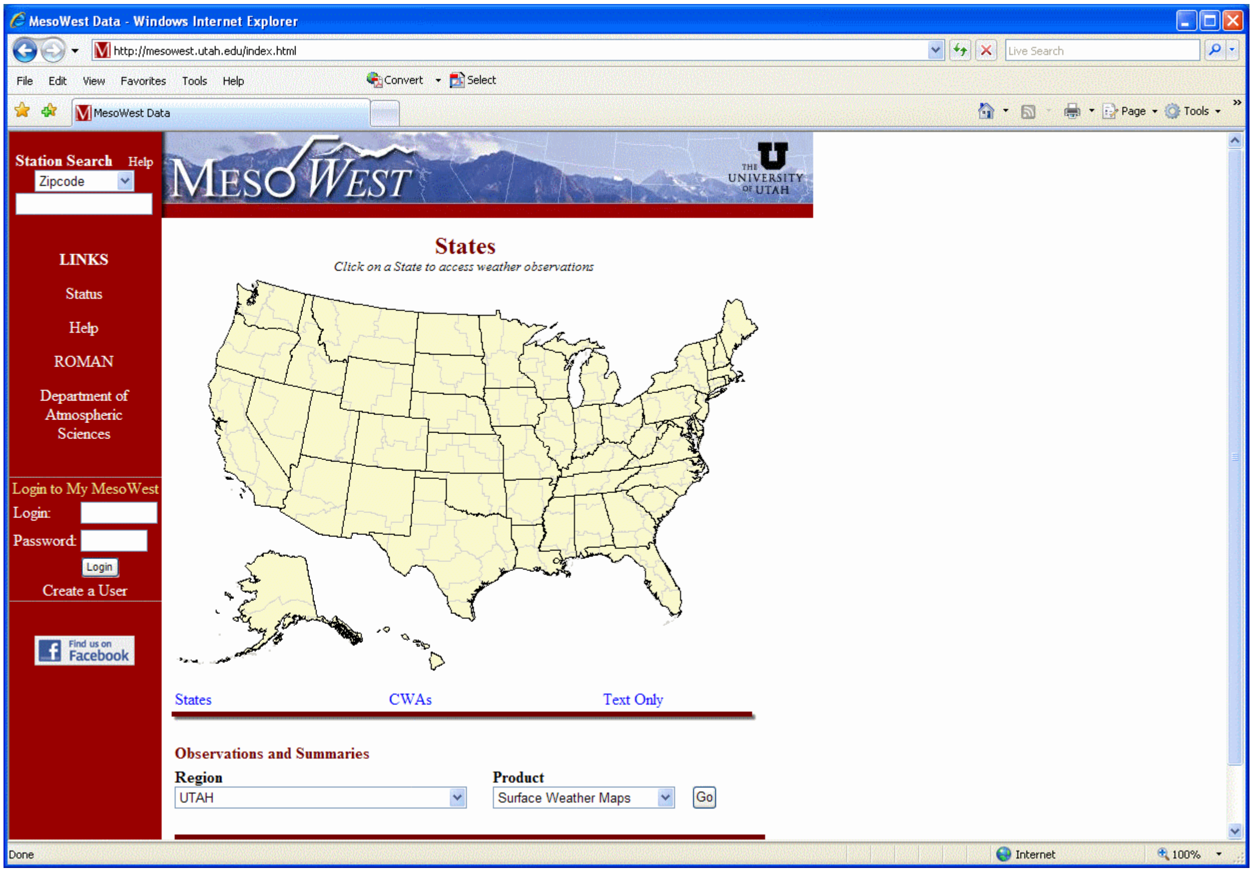


Figure 6. MesoWest Network website front-page. (Source: MesoWest, 2010).

air temperature, wind speed and direction, vector wind, wind rose, barometric pressure, event and accumulated precipitation, snow and solar radiation. Below the graph is a link to download the data as MS® Excel spreadsheet or a comma delineated text file. To view more than one day's data, the user must register, where a registered user can access 1, 10, 28, 29, 30, or 31 days of data dating back to 1997. The downloadable data include air and dew point temperature, relative humidity, wind speed, wind gust, wind direction, a quality flag, barometric pressure and solar radiation. Measurements are reported in five minute intervals. A logged-in user can access five day maximum and minimum values for temperature, humidity or wind speed for a single station, region or all stations in the state. Also, a current weather summary is available that displays the current air temperature, relative humidity, dew point temperature, wind speed and direction and peak wind speed along with 24 hour maximum and minimums and precipitation totals for one hour, three hours, six hours and 24 hour periods. These summaries are available for a selected region or the entire state.

Real-Time Observation Monitor and Analysis Network

The Real-Time Observation Monitor and Analysis Network (ROMAN) is very similar to the MesoWest network. This network was designed to provide current fire weather conditions primarily for the U.S. Forest Service. The website (see figure 7) is similar to MesoWest in appearance, navigation and data. The ROMAN network does include some sites that are not available to MesoWest and vice-versa.

Remote Automated Weather Stations

There are 71 Remote Automated Weather Stations (RAWS) located throughout Texas. These stations are operated by wild land fire agencies, federal, tribal, state and local entities. The federal agencies involved include the Bureau of Indian Affairs, the Bureau of Land Management, the U.S. Forest Service, the U.S. Fish and Wildlife Service and the National Park Service. These weather stations measure a ten minute wind speed average, maximum hourly wind gust, hourly precipitation, hourly barometric pressure, soil moisture, ten minute wind direction average, air temperature, ten minute relative humidity average and fuel moisture and temperature on some

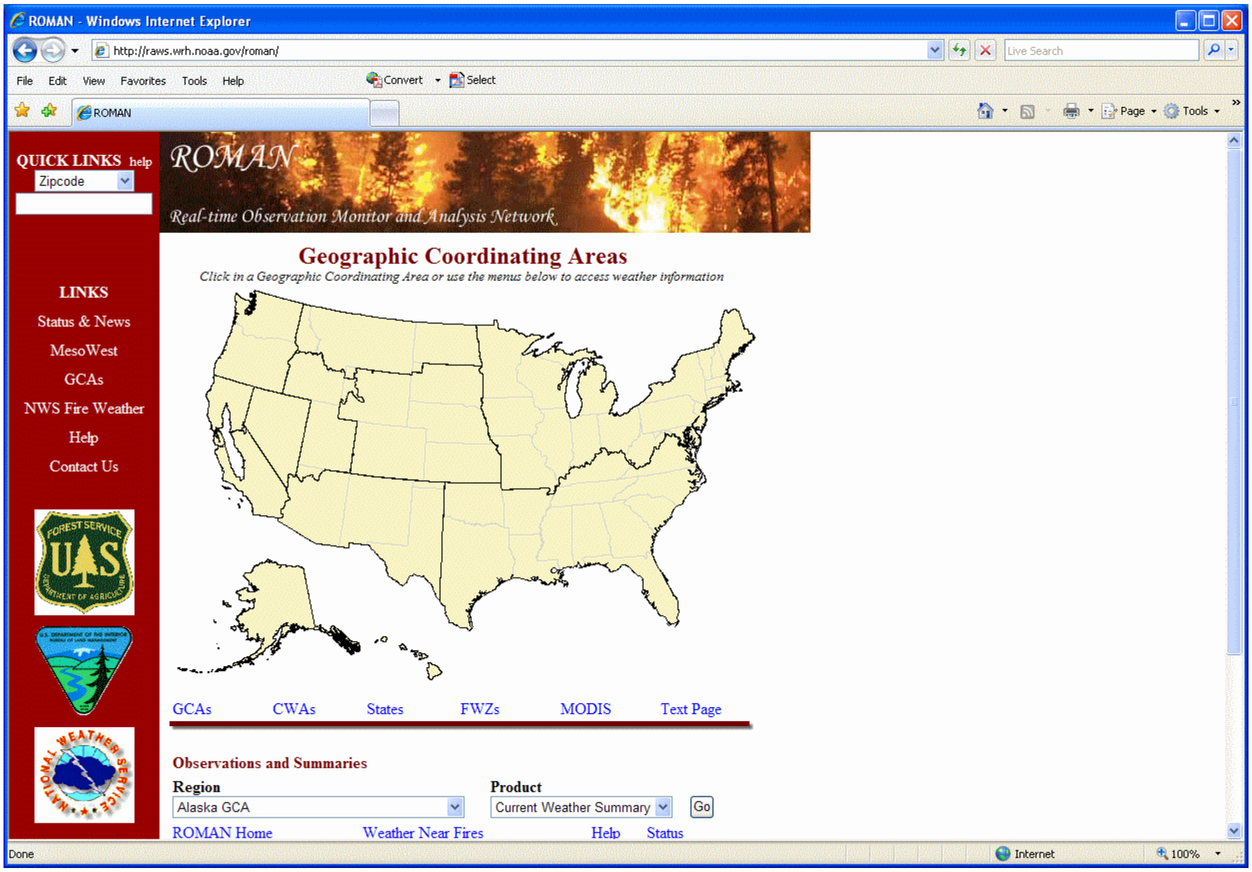


Figure 7. ROMAN Network website front-page. (Source: ROMAN, 2010).

stations. The data are collected and stored by a data logger and are transmitted by satellite every hour or three hours. Access to RAWS data is not available from the RAWS website, however, there are other weather station networks that access RAWS data and make them available to the public. The RAWS stations (see figure 8) in Texas are located at Anahuac, Aransas, Athens, Attwater, Barnhart, Bastrop, Balcones, Bird, Bootleg, Brazoria, Caddo Lake, Caprock, Caddo, Cedar, Cedar Hill State Park, Chisos Basin, Clarksville, Coldsprings, Coleman, Colorado Bend, Comanche, Conroe, Caprock State Park, Davis, Dayton, Dreka, Falcon Lake, Fort Davis, George West, Gilmer, Granbury, Greenville, Guadalupe Peak, Guadalupe River State Park, Henderson, Hamby, Huntsville, Kickapoo Caverns State Park, Kirbyville, Laguna Atascosa, LBJ Rd, La

Grange, Linn-San Manuel, Linden, Santa Ana, Lufkin, Matador, Mason, Matagorda Island, McFadden, McGregor, McKittrick, Midland, Miller Creek, Paint Creek, Palestine, Panther Junction, Pearsall, Pinery, Possum Kingdom, Ratcliff, Round Prairie, San Bernard, Sabine North, Sabine South, Southern Rough, Temple, Texarkana, Victoria, Woodville and Yellowpine.

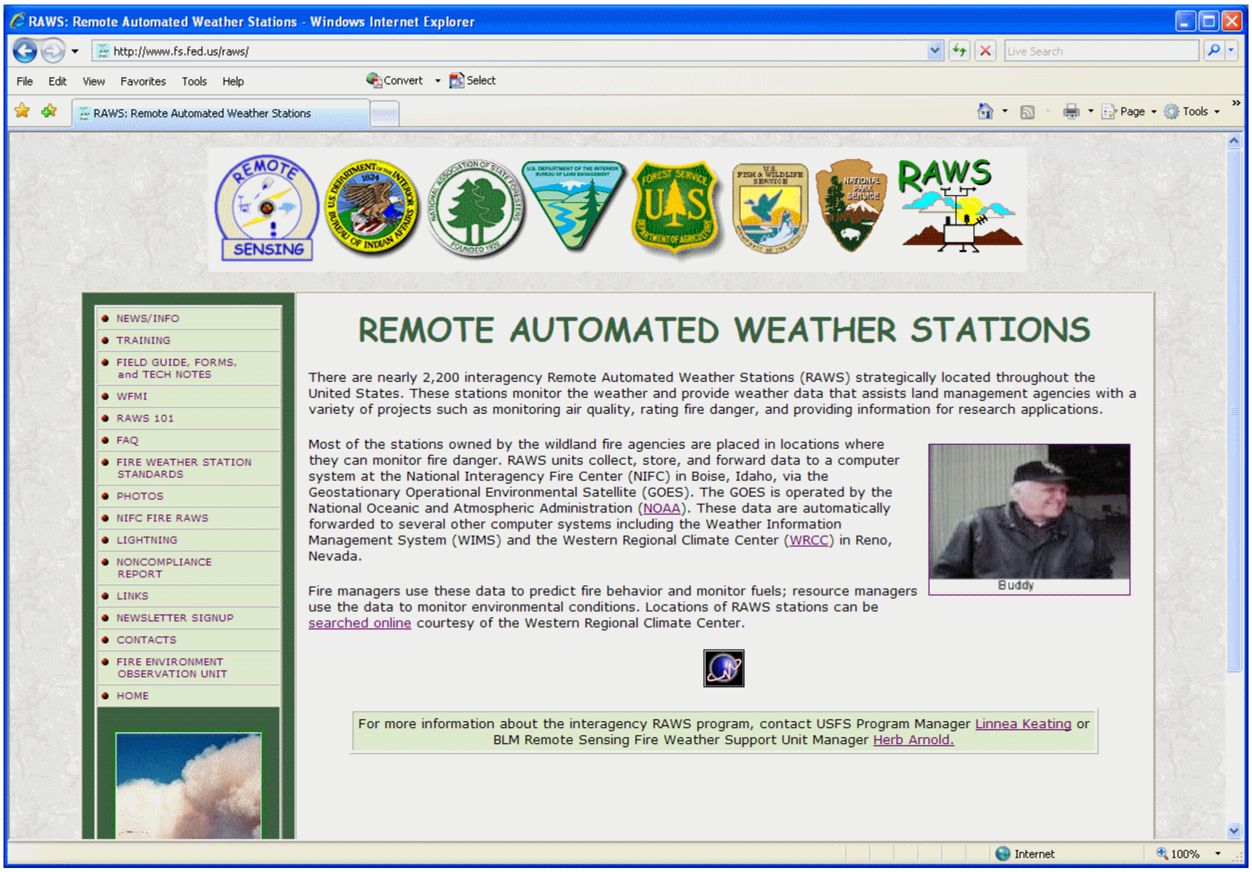


Figure 8. RAWS Network website front-page. (Source: RAWS, 2010).

Desert Research Institute

The Desert Research Institute (DRI) has an available RAWS climate archive for the state of Texas (see figure 9). The data available include daily summaries with or without wind chill and heat index, monthly summaries with or without ET data and data graphs among other options.

Another option is hourly data for a selected time period. These hourly data cannot be downloaded, however. Hourly measurements include average wind speed, wind direction, maximum wind speed, mean air temperature, mean fuel temperature, mean fuel moisture, relative humidity, dew point, wet bulb temperature and total precipitation. The hourly data are available for one day or a selected date range period. Hourly data for dates more than 30 days old cannot be accessed from the website, but are available to certain groups or individuals upon request. Daily data for multiple days are available and can be displayed graphically. Daily data can be displayed for any selected date range from one day to every day for which the selected site has data. Monthly data summaries are also available for one month or a selected range of months.

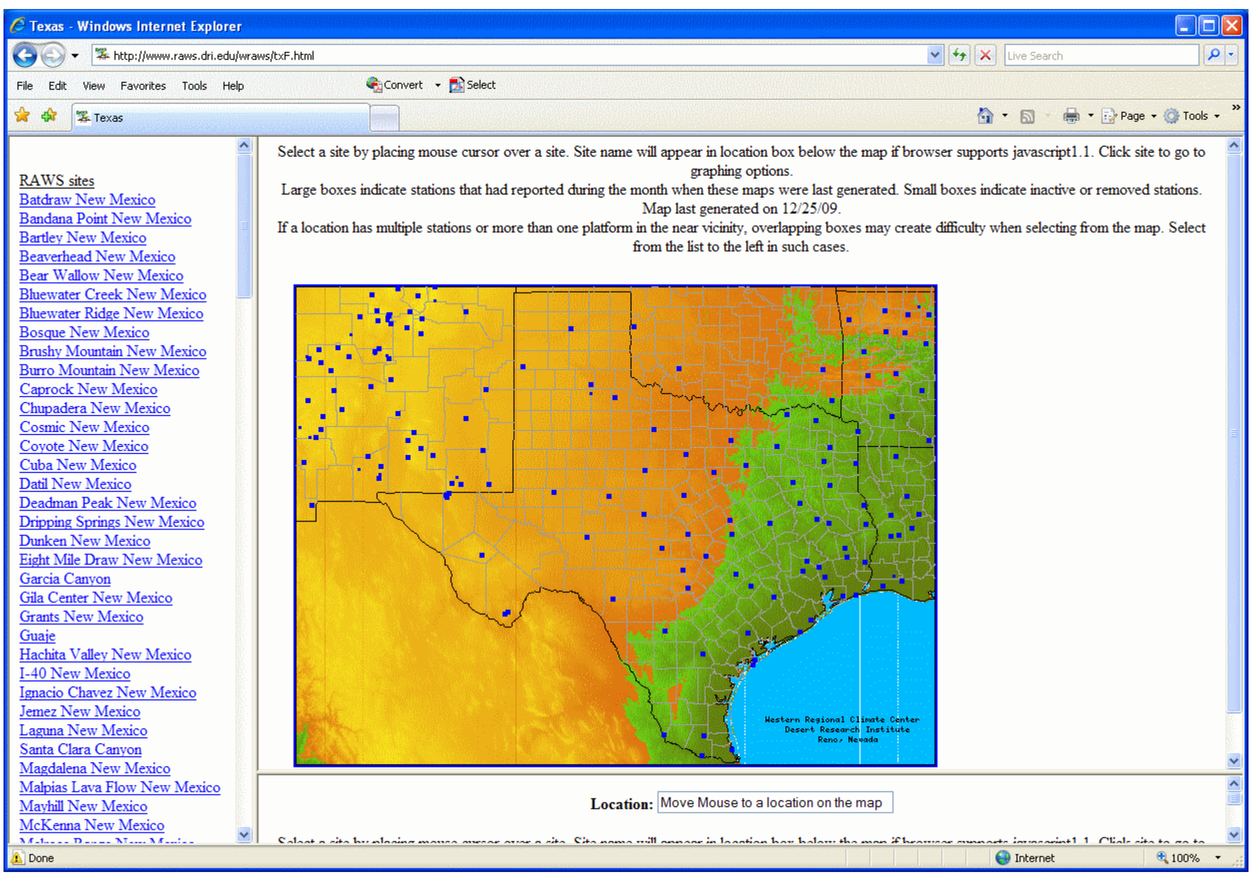


Figure 9. Desert Research Institute website front-page. (Source: DRI, 2010).

Integrated Agricultural Information and Management System

The Texas A&M AgriLife Research Center at Beaumont operates an integrated Agricultural Information and Management System (iAIMS) website (see figure 10) that offers weather, climatic and soil data. The climatic data tool displays hourly or daily data for the selected years. The data measured are maximum, minimum and average air temperature in degrees Fahrenheit;

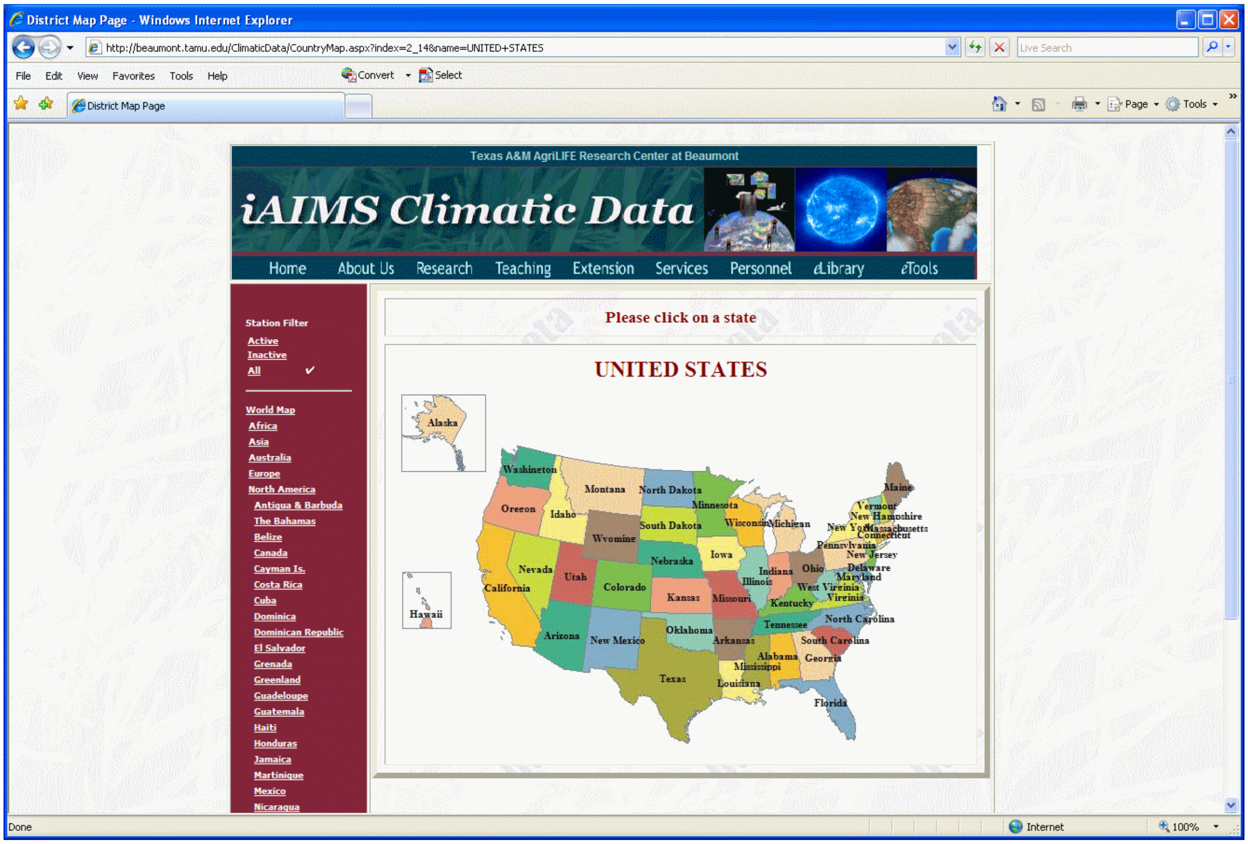


Figure 10. Integrated Agricultural Information and Management System website front-page. (Source: iAIMS, 2010).

rainfall in inches; wind speed in miles per day; wind direction; maximum, minimum and average relative humidity as a percentage; solar radiation in megajoules per square meter per day; average, maximum and minimum soil temperature in degrees Fahrenheit; reference evapotranspiration and pan evaporation in inches. Not every measurement is recorded at every station. The default display is a graph of average air temperature and rainfall, however the data can be displayed in a table on the webpage and can be downloaded as a text or MS® Excel file. The iAIMS network does not operate or maintain any weather stations but gathers data from other data sources. This is essentially a virtual (electronic) network.

Weather Underground

Weather Underground is a website (see figure 11) that allows access to historical weather data from 1,573 stations across Texas. The user can select from a list of available stations or enter a location from which to retrieve data. When a station is selected from the list, the website displays daily data that include current, high, low and average values of air and dew point temperature, relative humidity, wind speed, wind gust, wind direction, barometric pressure, precipitation, solar radiation and UV index. Measurements are displayed in units of degrees Fahrenheit for air and dew point temperature, percent for relative humidity, miles per hour for wind speed and gust, inches of mercury for pressure, inches for precipitation and watts per square meter for solar radiation. The date of the daily data can be selected to show the values from any date since January 1, 2008. Five minute data are also available for the parameters listed above and these data and can be downloaded in a comma delimited text file, table or graphical format. Fifteen minute observations are available as are weekly, monthly, yearly and custom timeframe summaries. Each of these include high, low and average values for air and dew point temperature, relative humidity, wind speed, wind gust, wind direction, barometric pressure and precipitation; graphs are available for these values. Below the graphs are more detailed daily measurements which include high, low and average values for air and dew point temperature, relative humidity, sea level pressure, visibility in miles, wind, gust speed and a sum of precipitation.

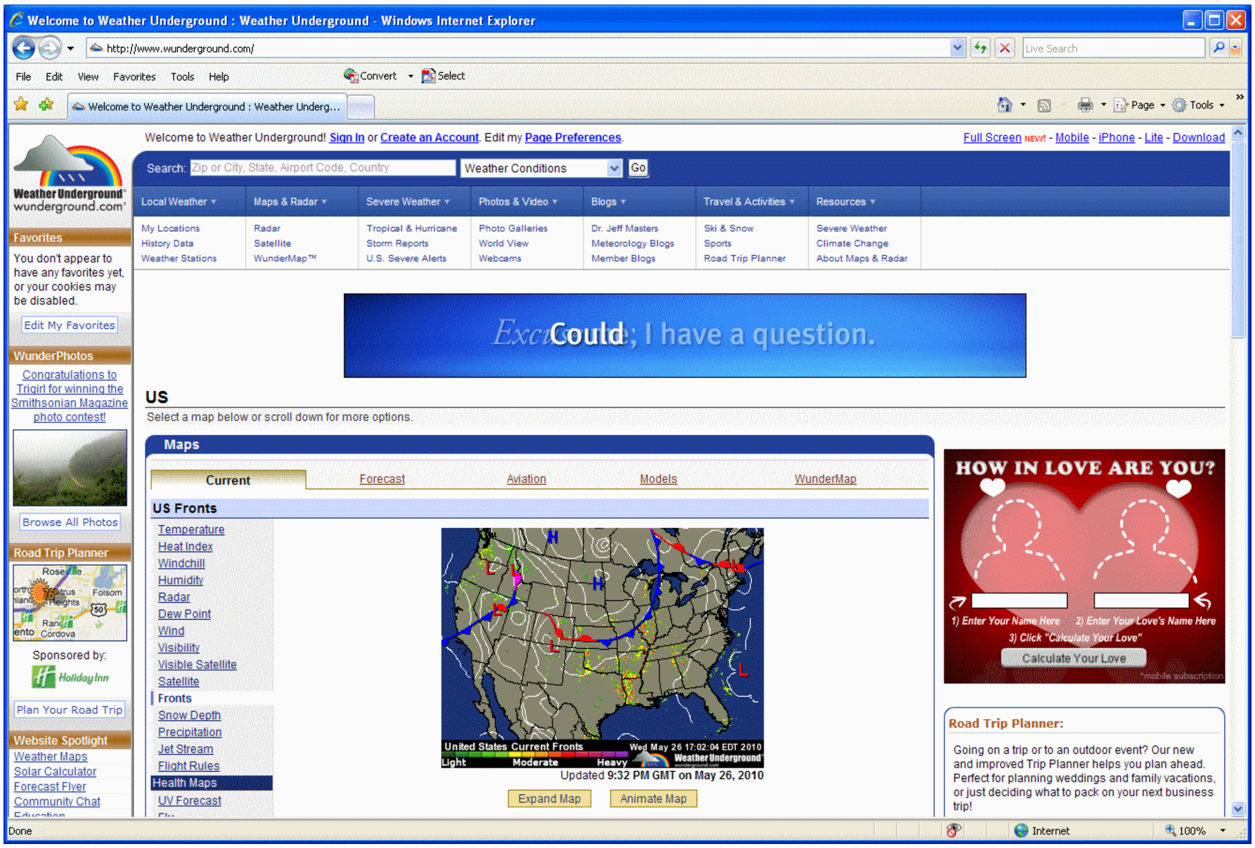


Figure 11. Weather Underground website front-page. (Source: WU, 2010).

Entering a city and state rather than selecting a station from the list will produce a slightly different report. This report contains daily, weekly, monthly or custom summaries which include minimum, maximum, mean air temperatures; heating degree days,; month to date heating degree days; since July 1 heating degree days; cooling degree days; month to date cooling degree days,; year to date cooling degree days; growing degree days; dew point temperature; average, maximum and minimum relative humidity; precipitation; month to date precipitation; year to date precipitation; snow; month to date snowfall; since July 1 snowfall; snow depth; sea level pressure,; wind speed,; maximum wind speed; maximum wind gust; visibility and event notes. Actual, average and historical record data are available for some measurements.

The Texas AgriLife Research and Extension Center at Overton

The Texas AgriLife Research and Extension Center at Overton operates a single weather station to provide weather and potential evapotranspiration data (see figure 12) for the Sabine River

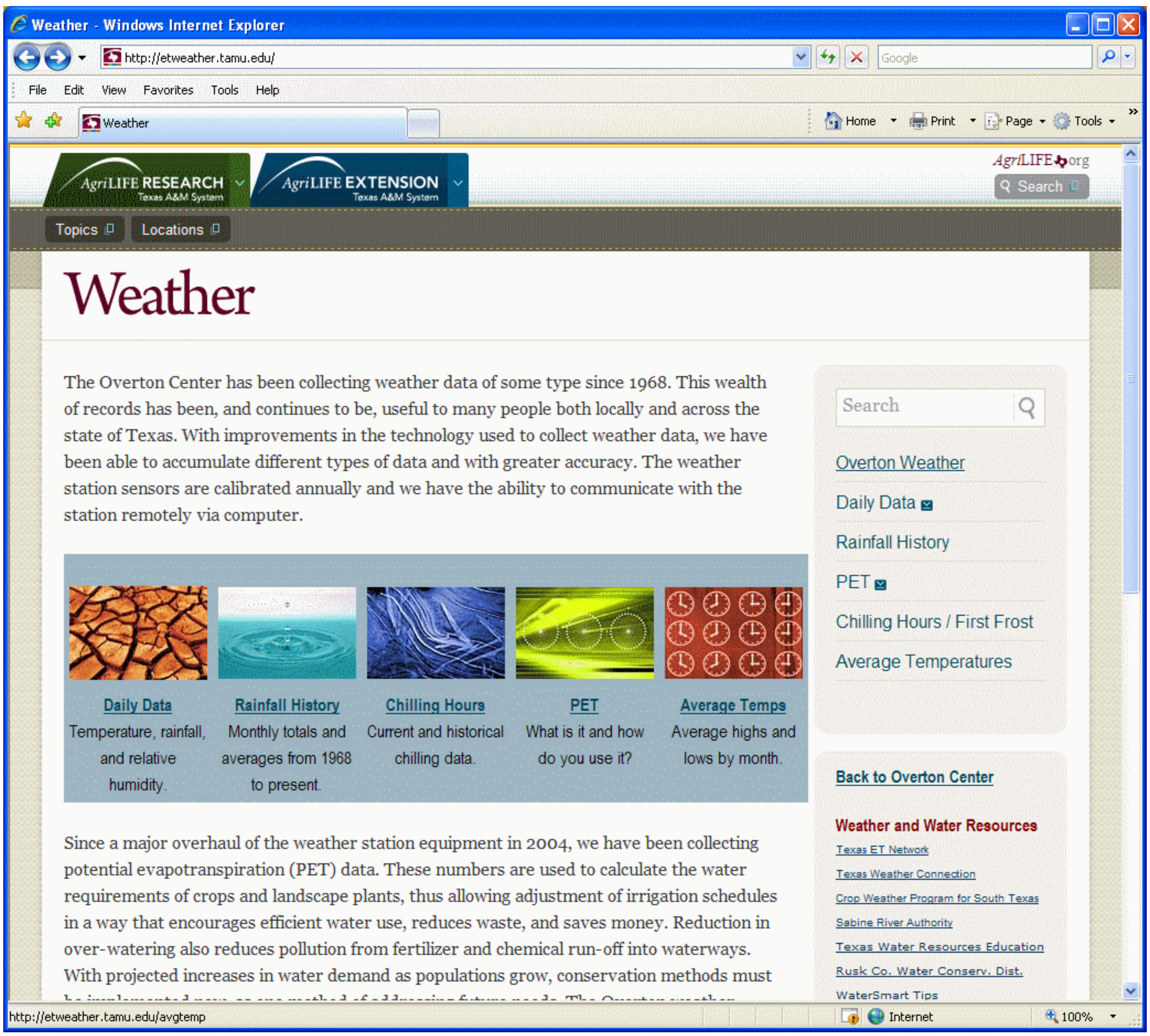


Figure 12. Texas AgriLife Research and Extension Center at Overton website front-page. (Source: TARO, 2010).

Basin and greater northeast Texas area. Daily measurements for this station include maximum, minimum and average air temperature; maximum and minimum relative humidity; total daily solar radiation and total rainfall. The units of measurement are degrees Fahrenheit for air temperature, percentage for relative humidity, megajoules per square meter for solar radiation and inches for rainfall.

This website also displays total and average rainfall by month and year since 1968. Another dataset is available for chilling hours and the annual first frost date for each season since 1997, as well as the first frost air temperature and chilling hours calculated by two methods. Another available page is the PET data page. This page provides PET data from the station at Overton and from the Texas ET Network. PET data are displayed for the current month next to a calculator to allow for easy calculation for any number of days. Historical PET data are available since 2004 and the PET values are provided daily for each mont. The average page is another website page that provides air temperature data. These data include monthly high, low and average air temperature values for each year since 1999 with historical values below the monthly data.

New Mexico Climate Center

The New Mexico Climate Center (NMCC) collects data from 194 weather stations throughout New Mexico. This network does not gather data from stations in Texas, but some stations are located close to the state line and could benefit users in either state. This is particularly true for the El Paso, Texas and Clovis, New Mexico areas. Surrounding Clovis is where much alfalfa is grown supporting the dairy industry in both states. The NMCC website (see figure 13) provides weather data and ET and hydrology tools as well as information on ET and drought reports. The weather data can be viewed graphically or tabularly and can be downloaded as a text file. The main parameters measured and reported are the maximum, minimum and mean values for air

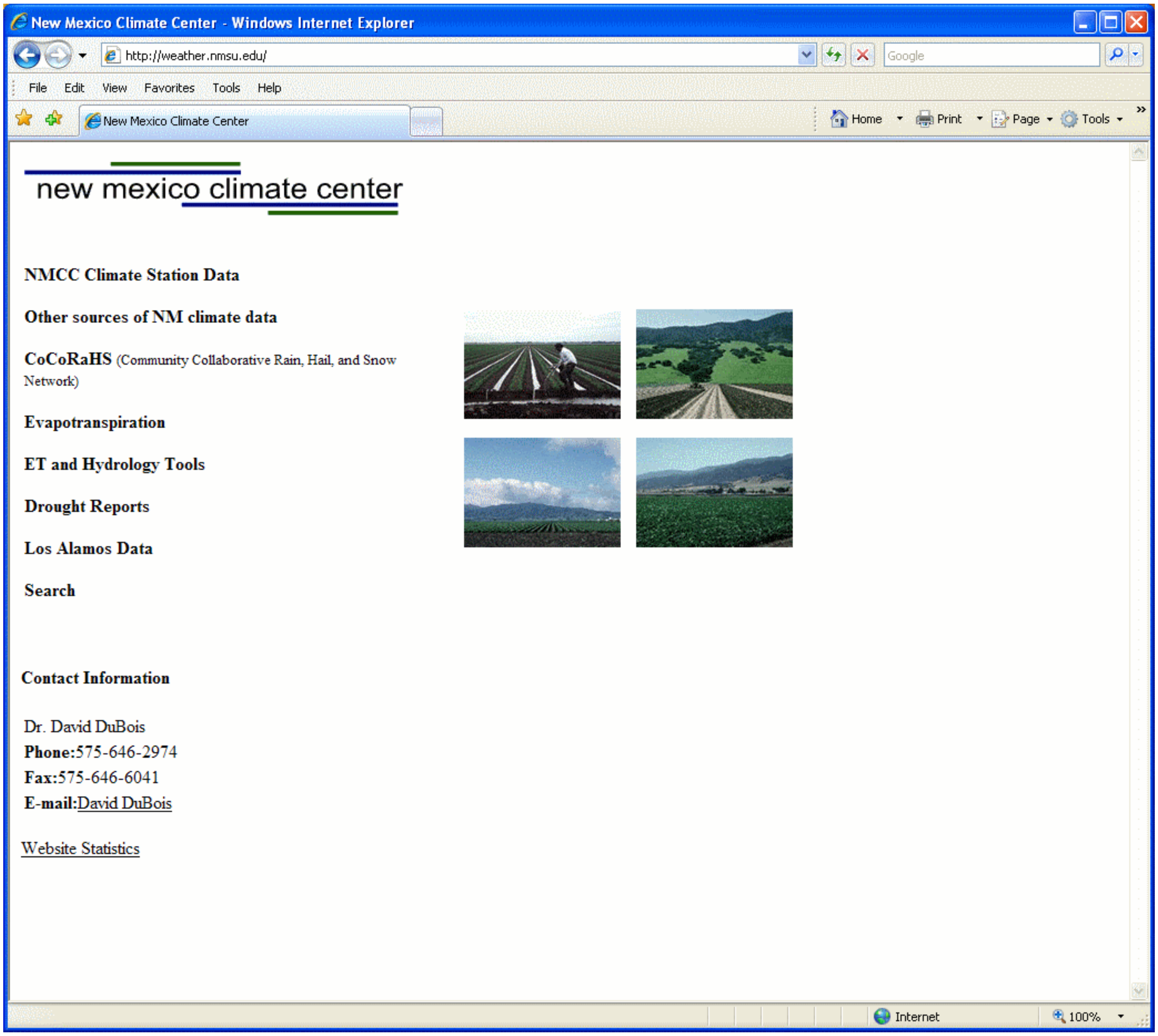


Figure 13. New Mexico Climate Center website front-page. (Source: NMCC, 2010).

temperature, relative humidity, precipitation, wind speed, wind direction, solar radiation and soil temperature. The units of measurement are degrees Fahrenheit for temperatures, inches for precipitation, percent for relative humidity, miles per hour for wind speed, degrees for wind direction and langleys per hour for solar radiation. (One langley is equal to one gram-calorie per square centimeter. A gram-calorie is the amount of heat required to raise the temperature of one gram of water one degree Celsius.) Not all NMCC stations measure all of the above parameters. The site's evapotranspiration information page provides information for a variety of crops including alfalfa, barley, chile, corn, cotton, grasses, grapes, lettuce, peanuts, pinto beans, onions, potatoes, pumpkins, rangeland, riparian vegetation, salt-bush atriplex (known by the common names of saltbush or orache), sorghum, soybeans, trees, wheat and related pest management concerns.

For these crops, the site provides water production functions, crop coefficients and irrigation schedules. Additional information is provided for selected crops. The water production function link displays a chart plotting grain yield against seasonal ET (see figure 14). The crop coefficient link displays a chart plotting crop coefficient against growing degree days for multiple locations. The site's irrigation scheduler is a spreadsheet for calculating and planning irrigation events and amounts. The ET and hydrology tools link displays a list of links to soil information, a water quantity model, climate models, ET calculator and other associated tools.

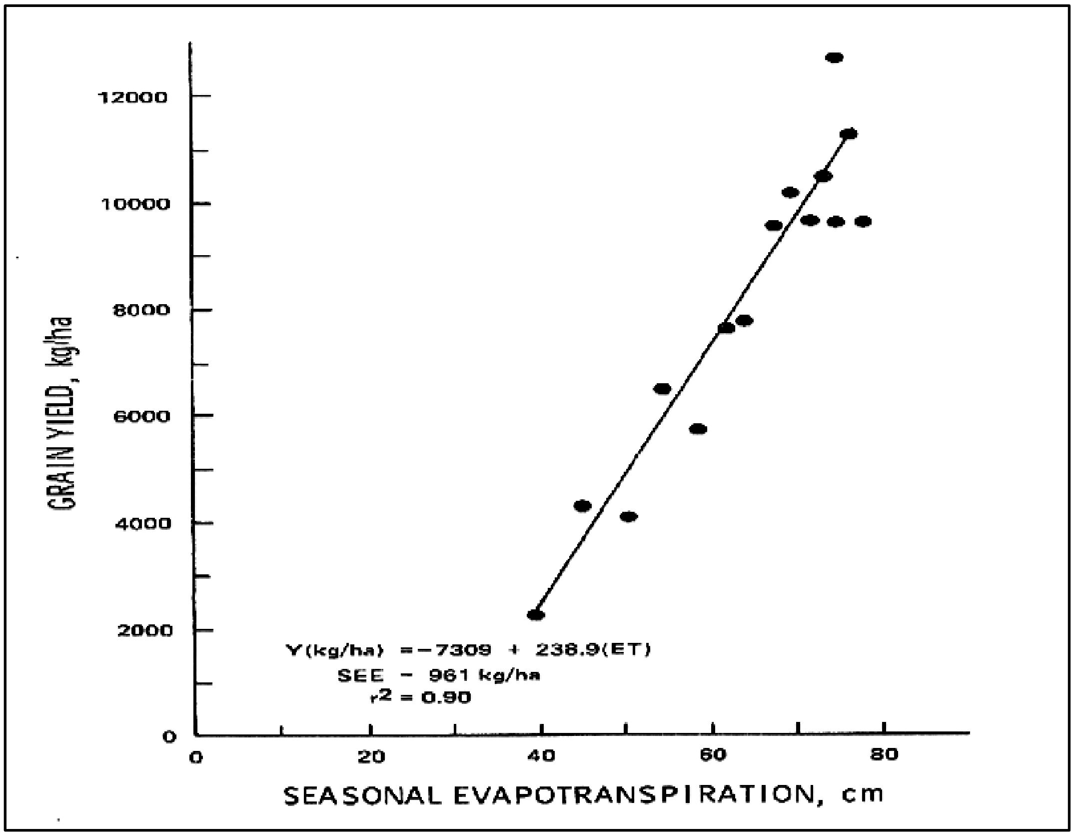


Figure 14. Example NMCC water production function graph. (Source: NMCC, 2010).

Iowa Environmental Mesonet

At first it would appear odd that a project dealing with assessing networks in Texas would be concerned with or reporting on an Iowa based data system. As it turns out, several networks around the country, such as iAIMS, gather data from meteorological stations around the country, including Texas, and act as clearinghouses of the data. Some of these type networks do not operate or maintain any physical stations but rather merely acquire and provide access to the data without any QA/QC. Nonetheless, some do offer a source of data for potential use for ET applications.

The Iowa Environmental Mesonet (IEM) is a website (see figure 15) accessing 170 Automated Surface Observing System (ASOS) weather stations throughout Texas. These weather stations measure air and dew point temperature in degrees Fahrenheit, relative humidity in percent, wind direction in degrees, wind speed in knots, solar radiation, altimeter reading in inches of mercury, daily and monthly precipitation in inches and wind gusts in knots. The data are collected hourly. Users of this website can select a station from a map of Texas or select by the location name from a drop down menu. Once a station is selected, the location of the station is displayed as a point on a map and latitudinal and longitudinal coordinates, as well as elevation and county.

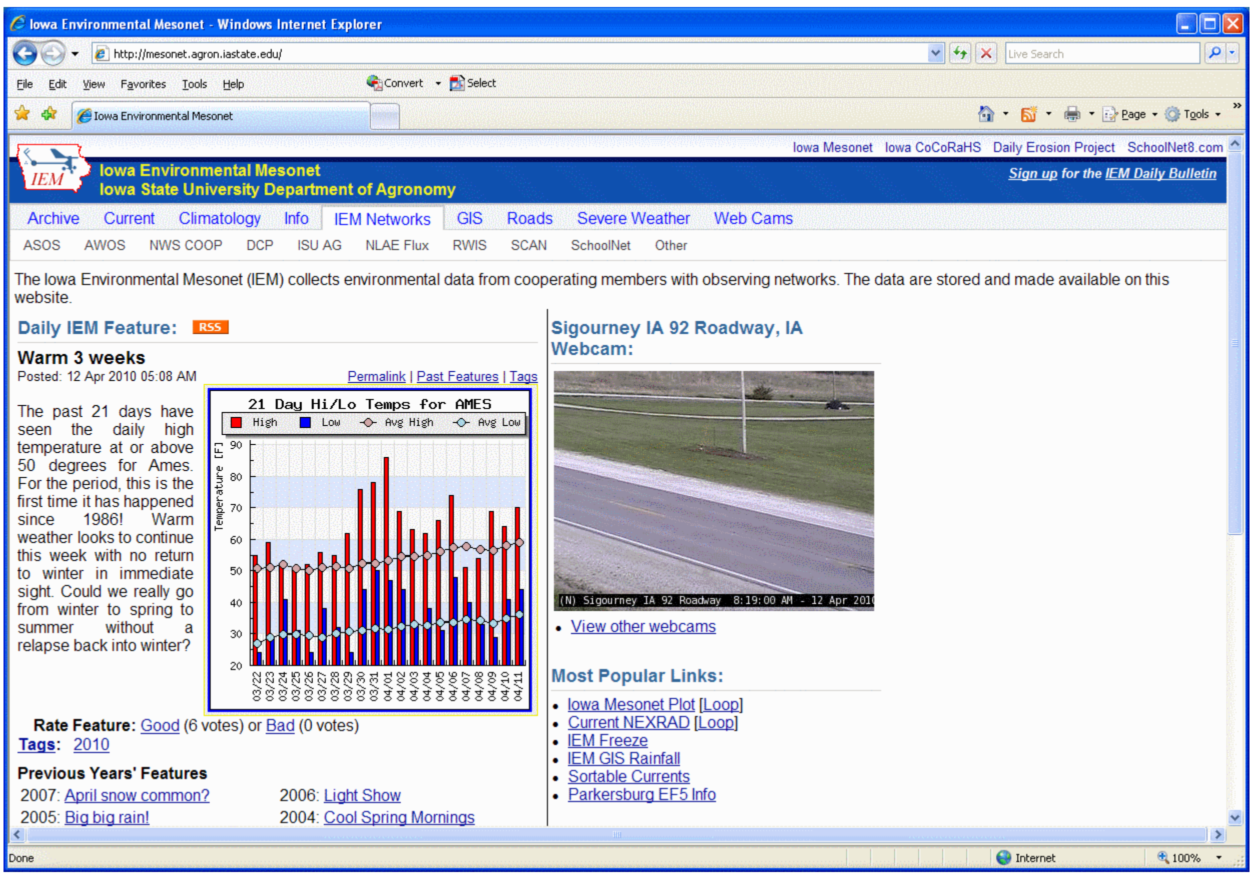


Figure 15. Iowa Environmental Mesonet website front-page. (Source: IEM, 2010).

There is a link that will display the last observations made by the station and the date and time of the measurements. There is another link that will display the names and types of stations that are within 25 kilometers (15.5 miles) of the selected station. There are also graphs available of the 7 day and monthly high/low air temperatures and monthly cumulative rainfall. Another feature from this page is a data calendar that shows the high and low air temperature, rainfall total and maximum wind gust and direction. This allows the user to view daily data for the entire month on one screen. Selecting one day from this calendar displays the data for all stations in Texas for that day. This site also allows users to compare data from two stations, and the stations can be selected from a map or a drop down menu. Once the sites are selected, the user selects which variable to be compared and a graph is displayed. The hourly data are available for download as a text file. The user selects the station from which the data will be collected, the measurements taken, the date range and the data format.

KVII School Net

The KVII School Net is a system of approximately 100 weather stations spread throughout the panhandle of Texas. These stations (see figure 16) provide real-time measurements of air and dew point temperature, wind chill, heat index, wind speed and direction, barometric pressure and trend, relative humidity and rainfall. Daily data are available for high and low air temperature, high wind speed, low wind chill, high and low relative humidity, high and low barometer values and rainfall. The daily data categories display data for the current day, previous day and year to date. These data are not downloadable, however the display format is an interactive map that shows the real time data and can display up to two user selected parameters. The parameters include air and dew point temperature, barometric pressure and trend, wind speed and direction, relative humidity, current rainfall, rainfall rate, wind chill, heat index, high and low air temperature, wind speed and direction, peak wind speed and rainfall for the current and previous day and year to date,. The measurements have default units of degrees Fahrenheit for temperatures, inches of mercury for pressure, inches for rainfall and miles per hour for wind speed. The units can be changed to degrees Celsius for temperature, millimeters or millibars for pressure, millimeters for rainfall, knots or kilometers per hour for wind speed. The site map shows all weather stations, but a single station can be selected to display a table of data for that station.

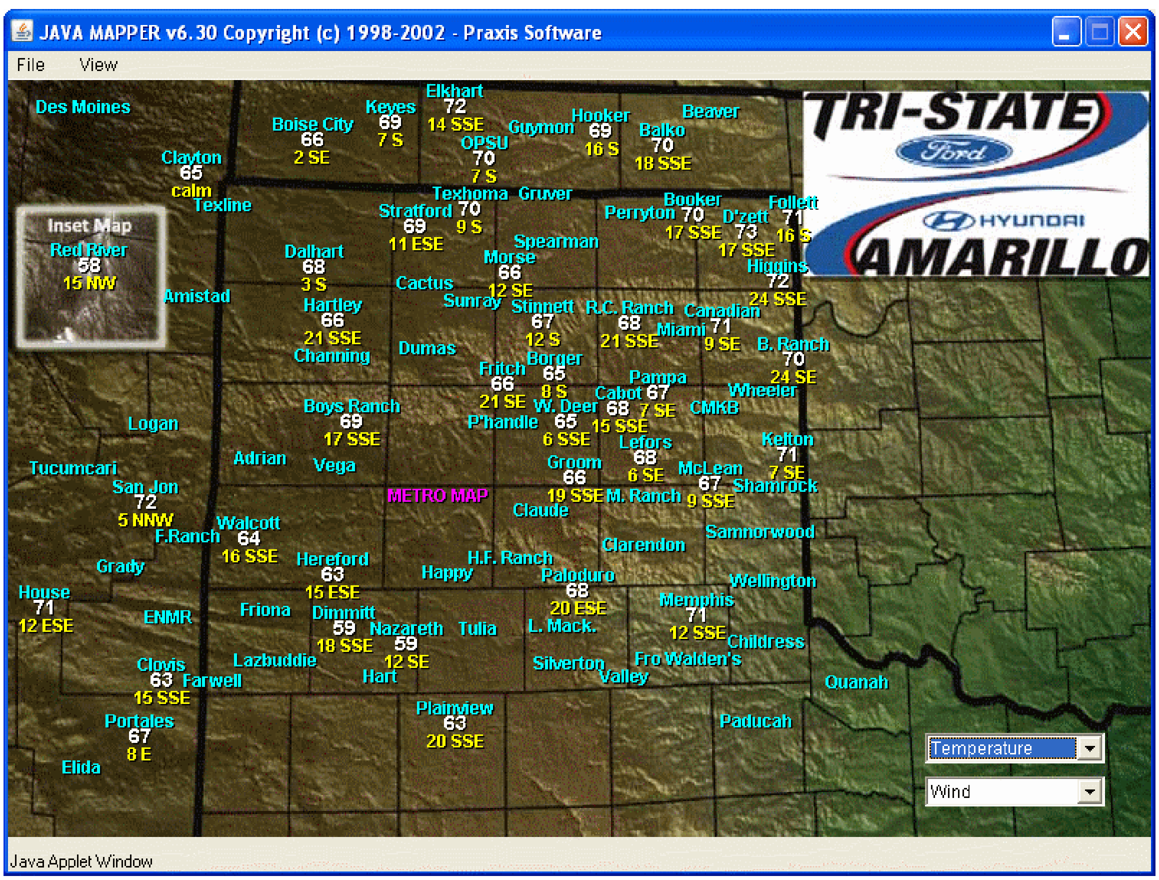


Figure 16. KVII School Net website front-page. (Source: KVII, 2010).

National Weather Service

The National Weather Service (NWS) is a division of the National Oceanic and Atmospheric Administration (NOAA) and operates a network of over 150 weather stations throughout Texas. These stations measure wind speed and gust in units of miles per hour, wind direction in degrees, visibility in miles, a description of the weather, sky conditions, air and dew point temperature in degrees Fahrenheit, six hour maximum and minimum for air and dew point temperature, altimeter pressure, sea level pressure and 1 hour, 3 hour and 6 hour precipitation. These measurements are displayed hourly. A summary can be accessed for the previous day and previous three days. The single day summary includes 6 hour and 24 hour maximum and minimum temperatures in both Fahrenheit and Celsius. In addition to the hourly measurements, the time can be selected to show the visibility and sky conditions for a selected hour. The three day summary is similar to the 24 hour summary but does not have options to select hours throughout the day. All values are displayed in columns and include all measurements taken and descriptions of weather, sky conditions and visibility.

The NWS website also provides climatology information (see figure 17). Reports can be generated including a daily climate report, preliminary monthly climate data, record event report and a monthly weather summary. The daily climate report shows the air temperature for the previous day, including the maximum, minimum and average values. The time for the maximum and minimum values is given along with the record values and the year of occurrence. Also the normal values are listed for all measurements with the difference from the normal and the values for that day from the previous year. Precipitation values are given on this report and include the previous day's precipitation, month to date, two month accumulation and three month accumulation. The record value for the previous day is displayed. Snowfall, heating degree days and cooling degree days are shown with the same parameters as precipitation, with the exception of snowfall and heating degree days. These measurements include month to date, two month accumulation and six month accumulation. Wind speed data include resultant wind speed and direction, highest sustained wind speed and direction, highest gust speed and direction and average wind speed, all in units of miles per hour. The average sky cover value is given along with relative humidity. The relative humidity values include highest percentage with time of

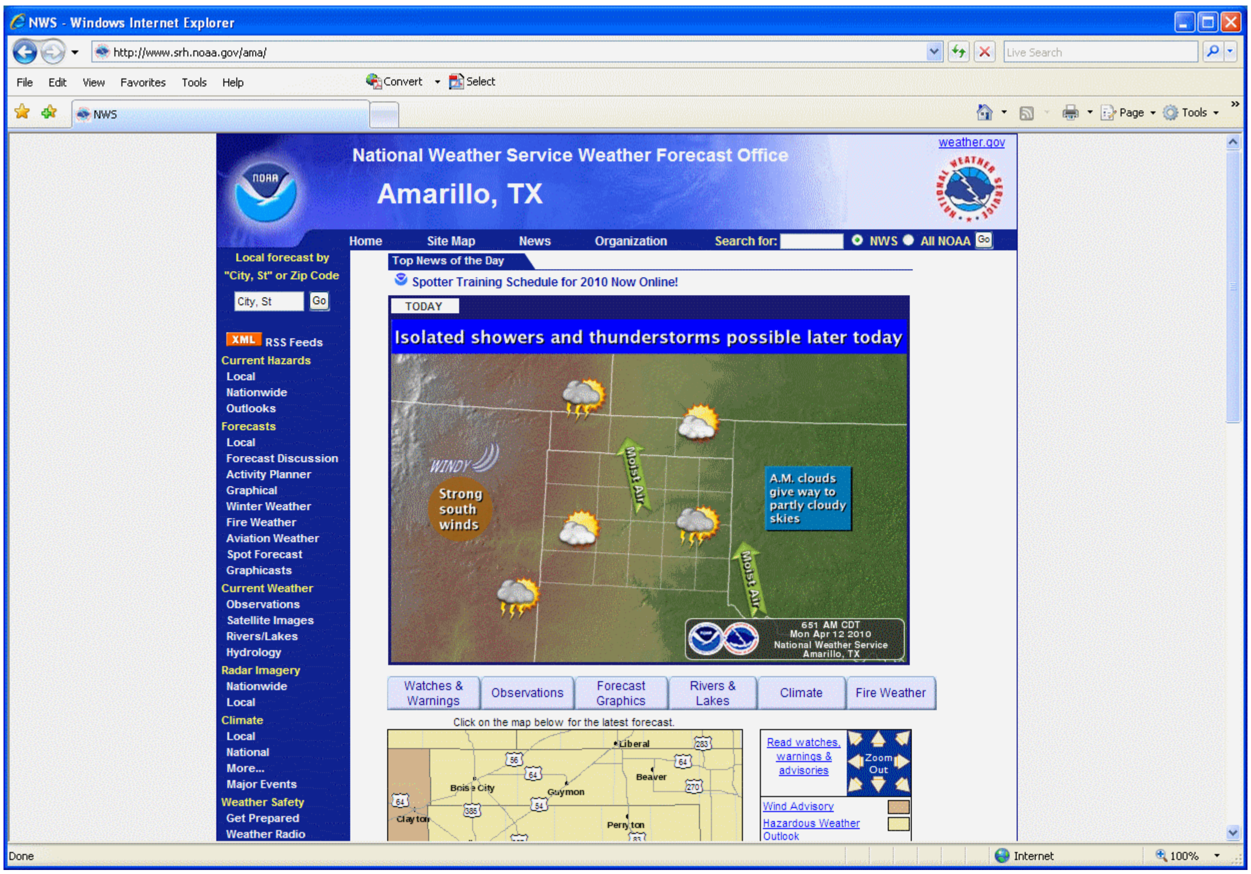


Figure 17. National Weather Service website front-page. (Source: NWS, 2010).

occurrence, lowest percentage with time of occurrence and average percentage. This report also includes the maximum and minimum normal and record values, with year of occurrence for the current date. Sunrise and sunset times are shown for the next two days. The daily climate reports are available for two months prior to the current day.

The preliminary monthly climate data report is available for a period of five years prior to the current month. This report includes maximum, minimum and average temperature; departure from normal; heating and cooling degree days; precipitation in water and snow; snow depth at 12z time (6 am CST); average, maximum and average wind speed; fastest 2 minute wind direction; minutes of sunshine; percent possible sunshine; sky cover; weather occurrences; peak wind gust and peak wind gust direction. A summation of certain measurements is provided below the daily values with averages for the measurements.

National Climatic Data Center

The National Climatic Data Center (NCDC) is a division within NOAA that archives data from 2,196 weather stations in Texas. The NCDC contains one of the most extensive and inclusive data warehousing centers in the world. Data cannot only be potentially used for ET based applications pertaining to agriculture but also in irrigation scheduling, hail probabilities and heat and cooling units for crop growth assessment analysis. Generally there is a several month delay in data availability.

A global summary of the day is available from the NCDC (see figure 18) which includes daily values for mean air and dew point temperature in degrees Fahrenheit, mean sea level pressure in millibars, mean station pressure, mean visibility in miles, mean wind speed in knots, maximum sustained wind speed and wind gust, maximum and minimum air temperature, precipitation in inches, snow depth plus fog, rain or drizzle, snow or ice pellets, hail, thunder and tornado/funnel cloud activity. These data are available for one or multiple stations and for any date range with the data available for download as a text file. Another available file is the preliminary record of climatological observations for each individual station. This file displays the maximum, minimum and observed air temperature in degrees Fahrenheit, precipitation in inches, snow, snow depth, wind movement (wind run) in miles, evaporation in inches, maximum and minimum 10.2 cm (4 in.) and 20.3 cm (8 in.) soil temperature with ground cover type, sum of precipitation and of snow. These values are displayed for each day of the current month. The original handwritten station report is also available. For a fee, station data are available that have undergone the NCDC quality control process. An annual subscription is also available for one to all stations for a fee. The monthly station climate summary provides data for temperature, precipitation, snow, freeze data, heating and cooling degree days and growing degree units. All data are based on normals and averages from 1971 through 2000. The temperature data include mean daily maximum, mean daily minimum and mean temperature for each month of the year. The growing degree units for corn are also listed using a base of 10/30 ^{o}C (50/86 ^{o}F) and this summary is available for download as a PDF file.

The monthly normals file contains data that include maximum, mean and minimum air temperatures for each month and the annual values for each station. This report also includes precipitation data detailing monthly and annual totals for each station and degree day data that includes monthly and annual totals for heating degree days and cooling degree days. The normals statistics included in this report give the highest mean, median, lowest mean, year of highest and lowest mean air temperature and maximum and minimum observation times for each month and the annual value. The monthly normals report is available as a PDF file or a text file.

The monthly precipitation probabilities file provides the probabilities of precipitation for each month and yearly total. The report is available as a PDF or text file.

Another available report is the annual degree days to selected bases report. This file is available in PDF or text format and contains annual heating degree days for the base air temperatures of 18.33, 15.56, 13.89, 12.78, 10, 7.22 and 4.44 ^{o}C (65, 60, 57, 55, 50, 45 and 40 ^{o}F). It also includes the cooling degree days for bases of 21.11, 18.33, 15.56, 13.89, 12.78, 10 and 7.22 ^{o}C (70, 65, 60, 57, 55, 50 and 45 ^{o}F).

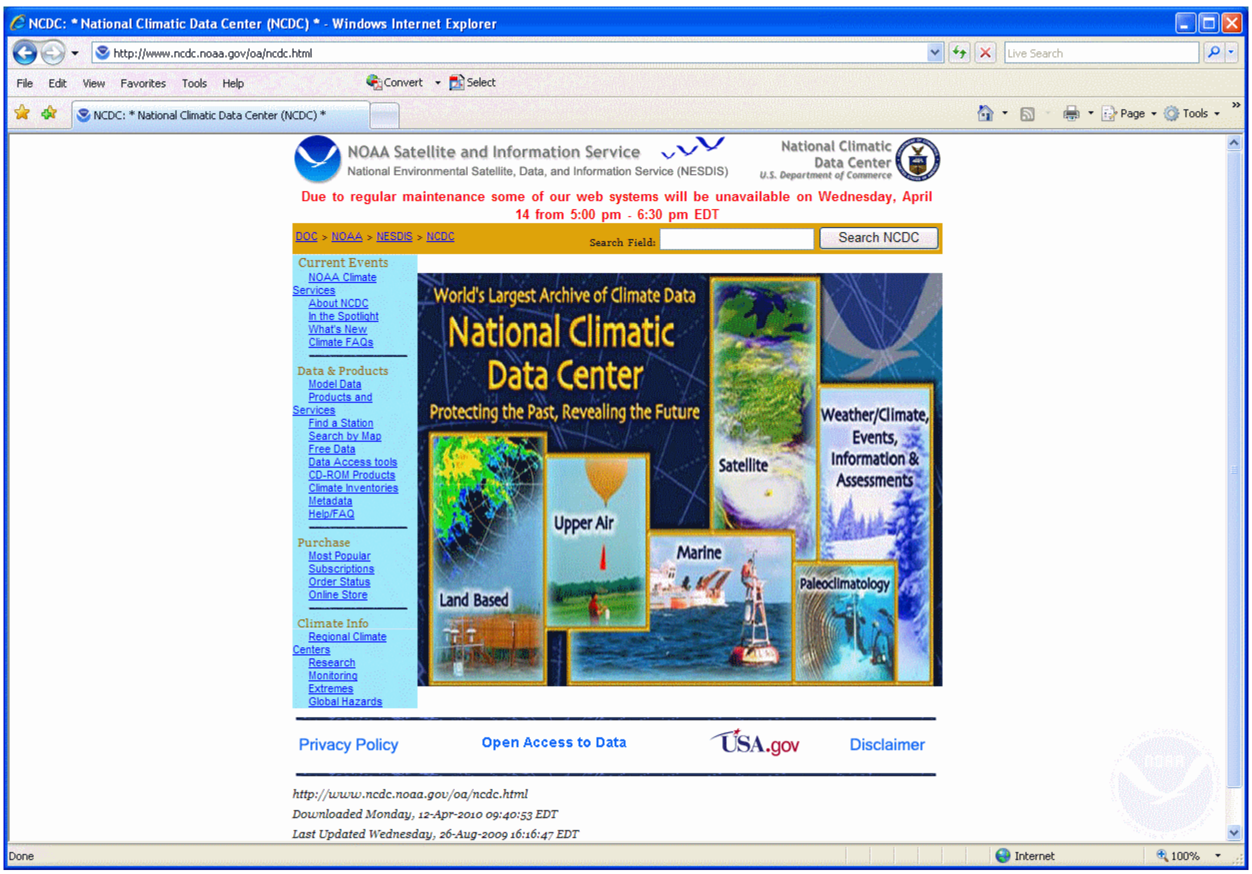


Figure 18. National Climatic Data Center website front-page. (Source: NCDC, 2010).

Midsouth Weather Network

The Midsouth Weather Network (MSWN) displays data from 30 weather stations throughout Texas, Oklahoma, New Mexico, Louisiana and Arkansas (see figure 19). Thirteen of these stations are located in Texas near the cities of Abilene, Cleveland, Decatur, Hawley, Mission, New Braunfels, Plano, Roanoke, Round Rock, San Angelo, Sanger, Tyler and Victoria. This is a network of personal websites for weather stations located in these five states. The majority of these stations is linked to or obtains data from Weather Underground or the National Weather Service. The MSWN website displays data from all member stations on the homepage. The displayed data include air and dew point temperature, relative humidity, average wind speed and gust, precipitation, barometric pressure and trend. The units of measurement are degrees Fahrenheit for temperature, percent for relative humidity, miles per hour for wind, inches for rain and inches of Hg for barometric pressure. There are links to the individual web pages for each of these stations from the MSWN website. Most of these sites only display current observations and do not archive the data; thus, current data cannot be downloaded. The stations that do archive data are Cleveland, Decatur, New Braunfels, Plano and Victoria.

The Cleveland, TX website archives daily data for air temperature, rain and wind. The archived air temperatures include highs and lows for each day of each month and are available from 1998 to present. Wind data available include average, high and direction from 2008 to present. Rainfall data are reported as daily totals.

The Decatur, TX site provides a table with daily data for a specified month. The table includes maximum, minimum, average, departure from normal values for air and dew point temperature, average wet bulb temperature, heating degree days, cooling degree days, sun hours, snowfall, rain, average sea level pressure, average and maximum wind speed and average wind direction. These reports are available from January 2002 to present.

The Victoria and New Braunfels sites provide the same data display for daily data. The data are displayed in a text based format that provides average values for air and dew point temperature, relative humidity, barometric pressure, wind speed and gust speed and wind direction. Also, rainfall for the month and year, maximum rainfall intensity per minute, maximum and minimum

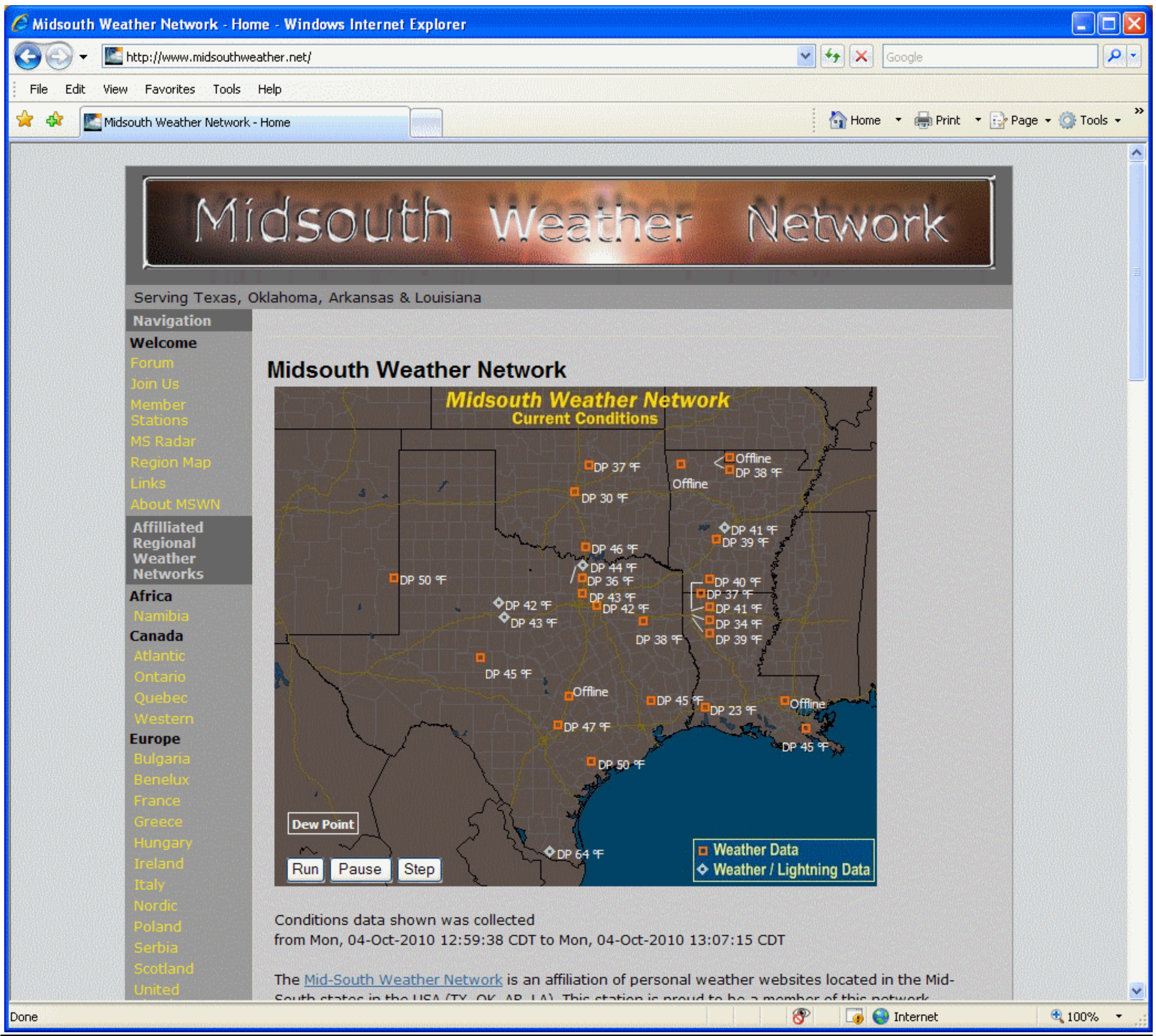


Figure 19. Midsouth Weather Network website front-page. (Source: MSWN, 2010).

air and dew point temperature, relative humidity, barometric pressure, wind speed and gust and maximum heat index and a plot of the previous 24 hour data are provided. The Plano, TX site provides two reports of daily data. The first is a local climatological datareport that is similar in format to the report that is given for the Decatur, TX site. The other report is a similar format to the report given for the Victoria and New Braunfels sites.

KVIA Weathernet Lab

An El Paso, TX television station, KVIA, operates the Weathernet Lab (see figure 20). This is a network of 17 weather stations located around El Paso. Current conditions are available for display only with no archived data available. This website interface is very similar to the School Net site of KVII in Amarillo, TX.

The parameters available are air and dew point temperature; barometric pressure and trend; wind speed and direction; relative humidity; wind speed, direction and chill; heat index; high and low air temperature; high wind speed; rainfall for the current and previous day; rainfall rate and annual rainfall. When the page is accessed, a map of El Paso with station locations is displayed. Below each station location on the map, current observations for two selected parameters are shown. Selecting a station will bring up a table with current conditions for all parameters. The units of measurement are degrees Fahrenheit for temperature, miles per hour for wind speed, inches for barometric pressure, percent for relative humidity and inches for rainfall

Figure 20. KVIA Weathernet Lab website front-page. (Source: KVIAWL, 2010).

United States Department of Agriculture

The USDA produces a weekly weather and crop bulletin (see figure 21) that displays color-coded maps of the United States. These maps include total precipitation in inches, crop moisture index, U.S. drought monitor, U.S. seasonal drought outlook, daily weather records, average soil temperature in degrees Fahrenheit, average pan evaporation in inches per day, extreme maximum and minimum air temperatures, departure of average air temperature from normal, total growing degree days and departure from normal growing degree days. Also included in the bulletin are weather data listed by state and station.

These stations provide numeric data for temperature in degrees Fahrenheit, precipitation in inches, relative humidity in percent and number of days with certain temperature and precipitation. Temperature measurements include average maximum, average minimum, extreme high, extreme low, average and departure from normal. Precipitation measurements include weekly total, departure from normal, greatest in 24 hours, total since March 1, percent

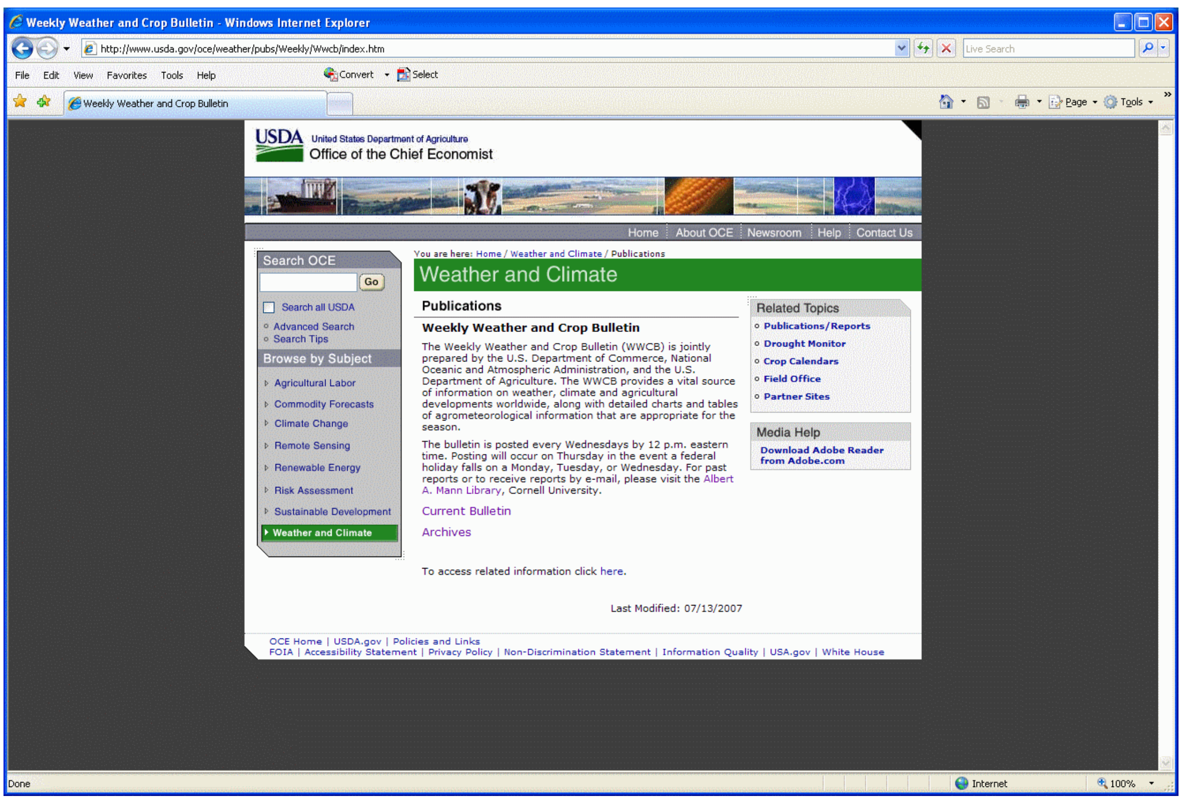


Figure 21. USDA Weekly Weather and Crop Bulletin website front-page. (Source: USDAWWCB, 2010).

normal since March 1, total since January 1 and percent normal since January 1. Relative humidity measurements include average maximum and average minimum. Also included are number of days with temperature of 32.2 ^{o}C (90 ^{o}F) and above, temperature 0 ^{o}C (32 ^{o}F) and below, precipitation 0.025 cm (0.01 in.) or more and precipitation 1.27 cm (0.50 in.) or more. In addition, a national agricultural summary is included in the bulletin. This summary provides a text description for different crops in terms of percentage planted, growth stages and crop conditions. This bulletin also provides short weather highlights and total precipitation maps for countries around the world. This bulletin is viewed on-line and can be downloaded as a PDF file. Archived files are available from 1971.

United States Historical Climatology Network

The United States Historical Climatology Network (USHCN) allows access to 49 weather stations throughout Texas. These stations are located in Albany, Alice, Alpine, Ballinger, Balmorhea, Beeville, Blanco, Boerne, Boys Ranch, Brenham, Brownwood, Catarina, Clarksville, Corpus Christi, Corsicana, Crosbyton, Danevang, Dublin, Eagle Pass, El Paso, Encinal, Falfurrias, Flatonia, Ft. Stockton, Gainesville, Greenville, Hallettsvile, Haskell, Lampasas, Liberty, Llano, Luling, Marshall, McCamey, Mexia, Miami, Muleshoe, New Braunfels, Paris, Pecos, Plainview, Quanah, Rio Grande City, San Antonio, Seminole, Snyder, Stratford, Temple and Weatherford. Data from these stations (see figure 22) are available for download as a comma separated file or as a user defined plot.

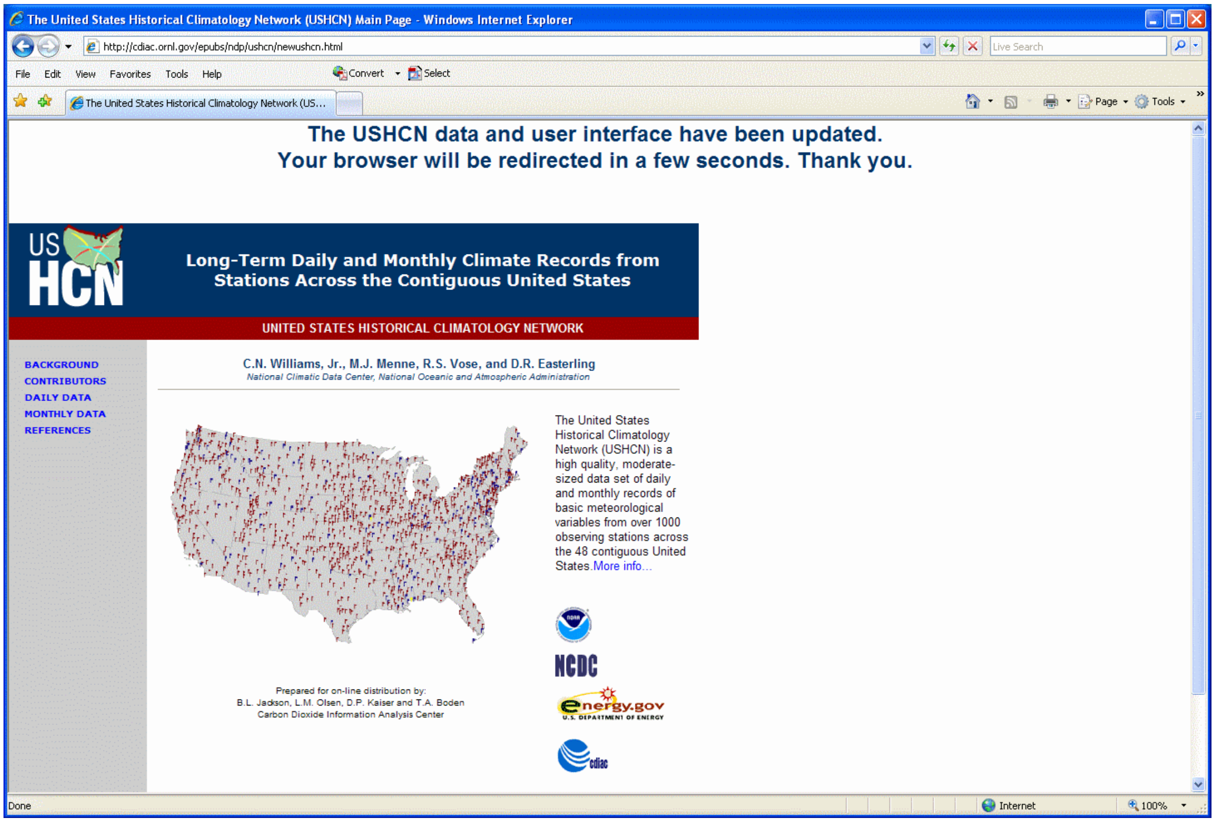


Figure 22. United States Historical Climatology Network website front-page. (Source: USHCN, 2010).

Daily measurements available for download include precipitation, precipitation flag, precipitation cumulative annual, precipitation cumulative by hydrological year, hydrological year, day of hydrological year, snowfall, snow flag, snowfall cumulative seasonal, snow depth, snow depth flag, snow season, snow season day, air temperature minimum, minimum flag, mean, maximum and flag. The user selects the date range for output. Monthly data include precipitation, annual cumulative precipitation, precipitation flag, hydrological year; maximum and minimum air temperatures and flags, mean and mean flag. The data also include annual and hydrologic average, minimum and maximum air temperatures and precipitation. Data are available from this site from years 1895 through 2008.

Lower Colorado River Authority

The Lower Colorado River Authority (LRCA) maintains 226 river gauges and weather stations along the Colorado River in Texas. These stations allow access to air temperature, rainfall, relative humidity, water flow, stage and lake levels. The data can be seen on an interactive map (see figure 23) that shows near real time data. These stations have a sampling and website update interval of 15 minutes. The interactive map known as Hydromet shows air temperature and relative humidity at 15 minute intervals for the past 14 days. The map also produces a graph of air temperature and relative humidity. Temperature is recorded in degrees Fahrenheit and relative humidity is in percent. The map can also display cumulative rainfall for the previous 14 days with rainfall displayed in units of inches. Archived data are available for viewing, but cannot be easily downloaded. Only one measurement can be displayed at a time for the historical data. Daily data are available including current, maximum, minimum and average air temperature; 1 hour, 3 hour, 6 hour, 24 hour and since midnight rainfall; and current, maximum and minimum relative humidity. These data are available for viewing, but cannot be easily downloaded. Each gauge is equipped with a small computer and radio equipment for data transfer over LCRA's radio towers.

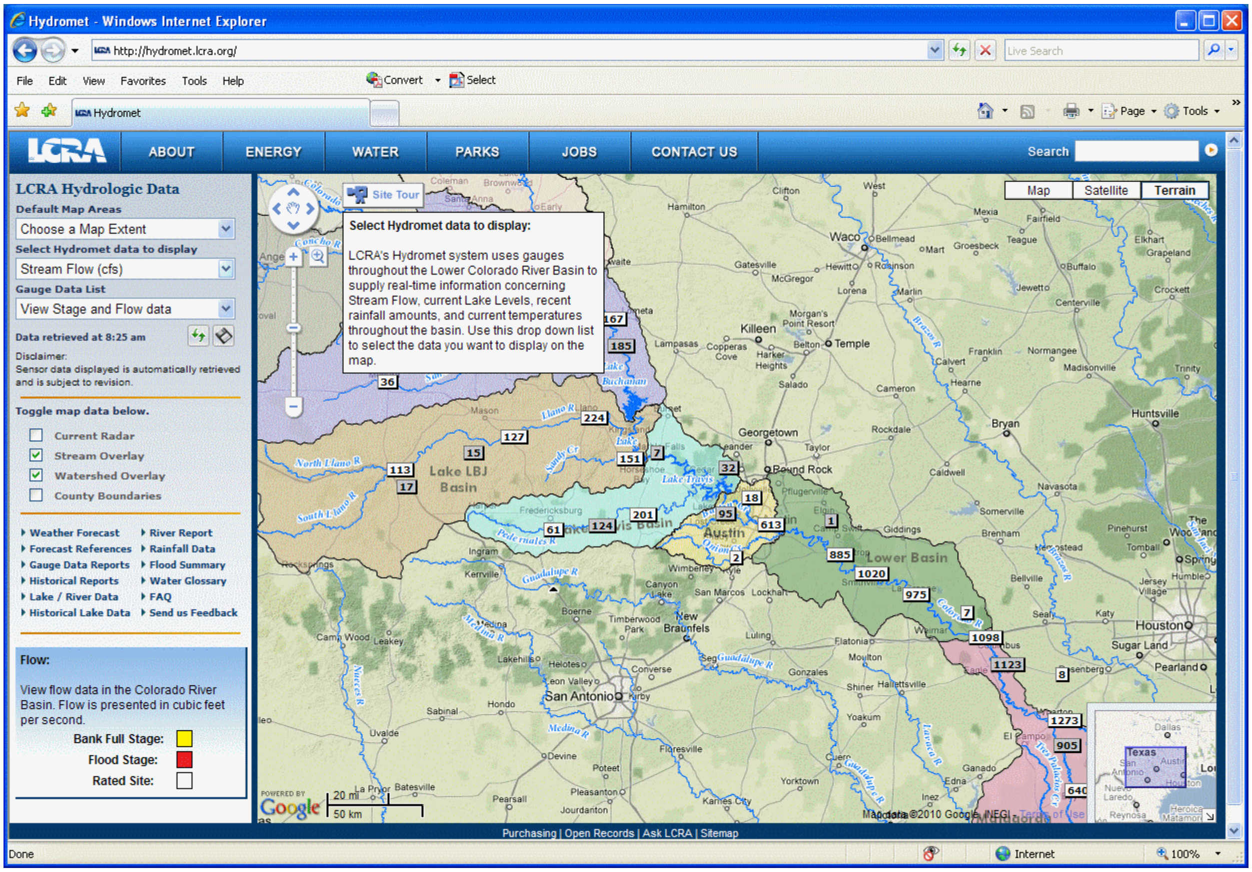


Figure 23. Lower Colorado River Authority Network Hydromet website front-page. (Source: LCRAN, 2010).

Community Collaborative Rain, Hail & Snow Network

The Community Collaborative Rain, Hail & Snow (CoCoRAHS) Network operates a system of 2,100 gauges (see figure 24). This network is a nonprofit organization that is operated by volunteers. The data are collected by volunteers who set up instruments at their location and are educated by CoCoRAHS. Once the data are collected, the volunteers enter their information into the website. This network measures precipitation (rain, snow and hail) only. The data are

Figure 24. Community Collaborative Rain, Hail & Snow Network website front-page. (Source: CoCoRAHS, 2010).

available in map form and daily or multi-day reports. The reports display total precipitation, new snow and total snow. All measurements are recorded in units of inches. There is also a daily comments report that lists comments made by the volunteer that operates each station. Significant weather reports give the duration of the event in minutes, new precipitation, total precipitation, new snow depth, total snow depth and flooding occurrence.

Hail data are available in a "Days with Hail Report," listing days with at least one hail report, searchable by either station number or location. In addition to the various reports, there are summary reports available. These reports include a station precipitation summary, station snow summary, total precipitation summary and “rainy” days reports. The station precipitation summary report is a list of precipitation data over a given date range for up to three stations. The station snow summary report is a list of snow data over a given date range for up to three stations. The total precipitation summary is a list of the total precipitation and number of reports for a given period for all stations. The rainy days report is a list of days in a given range with average precipitation, maximum precipitation and the number of stations reporting non-zero precipitation. The data are available for any requested day or time period in which the station was in operation. The data are available for viewing but cannot be downloaded.

Texas Coastal Ocean Observation Network

The Texas Coastal Ocean Observation Network (TCOON) is a system of forty-two weather stations along the gulf coast of Texas (see figure 25). These weather stations measure air temperature; water temperature; wind speed, gusts and direction; barometric pressure; cumulative rainfall; and secondary wind speed and gusts. Many of these stations are located close enough to the ocean to give water measurements. The measurements are taken at six minute intervals and are available as a graph, spreadsheet, text rows or text columns and the spreadsheet can be downloaded. The output interval for the data can be changed from the default six minute interval to half hour, hour, three hour, six hour, nine hour, twelve hour or daily at midnight. The website allows users to select data parameters of interest and customize graphical and tabular formats. The data are collected at the station and stored in the onsite computer. The data are then transmitted by satellite, spread-spectrum packet radio or telephone modem. Data are available from the date the station became operational to present.

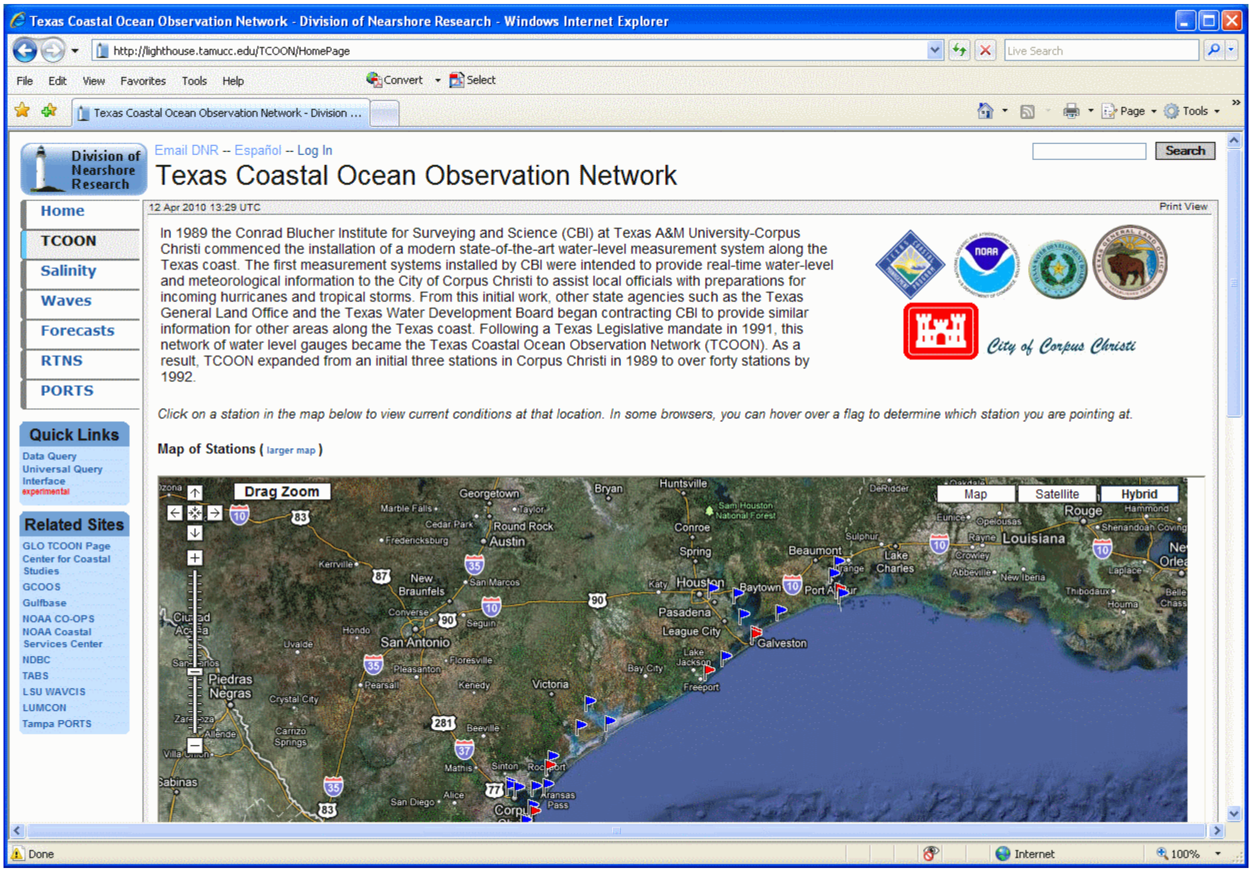


Figure 25. Texas Coastal Ocean Observation Network website front-page. (Source: TCOON, 2010).

Texas Commission on Environmental Quality

The Texas Commission on Environmental Quality (TCEQ) has weather data available (see figure 26) for viewing or download as a spreadsheet. These files are annual summaries which include hourly wind speed in units of meters per second, wind speed average in units of meters per second, wind direction in units of degrees and air temperature in units of degrees Celsius. For each variable, the file includes the unit of measurement, the method text description, method code, number of hours of valid data, if the data were valid for the day, the daily high and the hourly average. Data are available for 1973 through 2006.

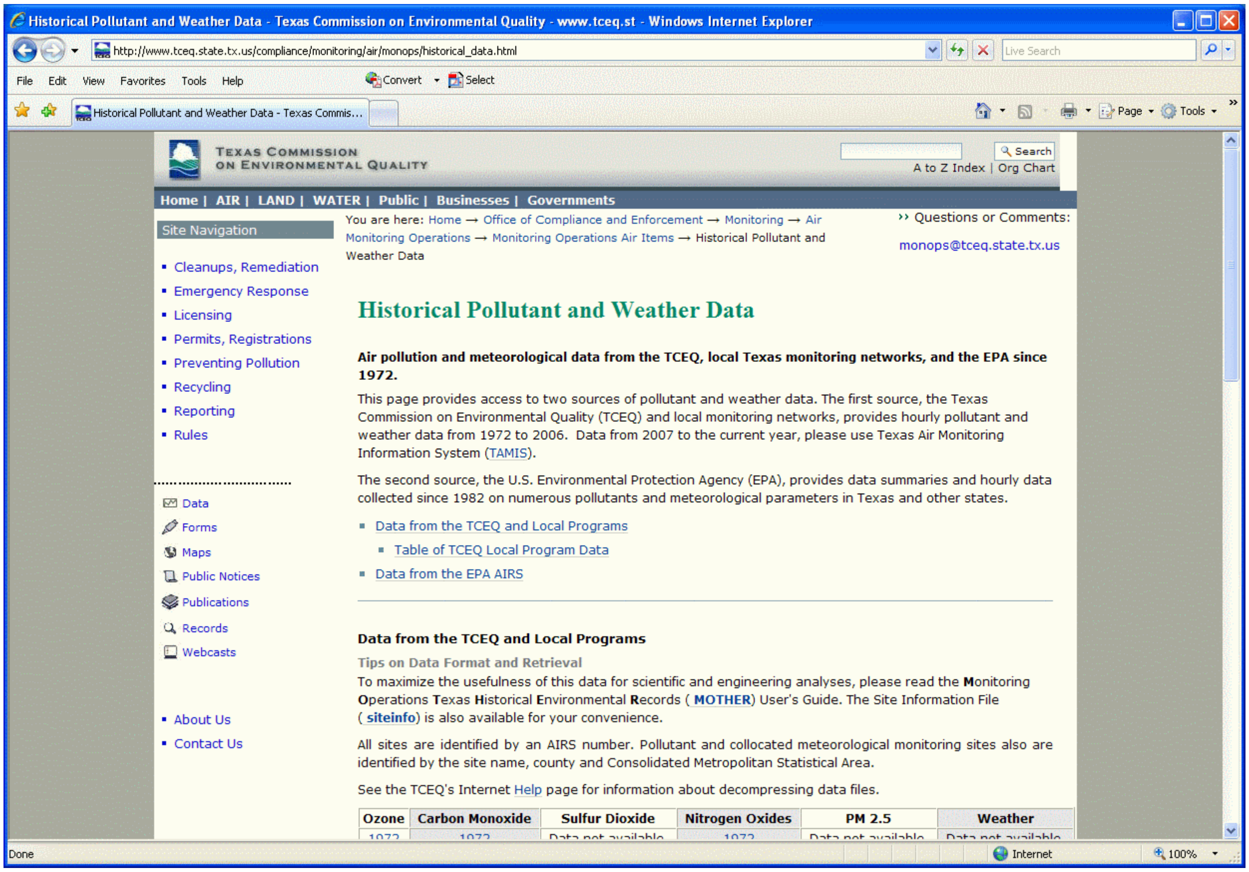


Figure 26. Texas Commission on Environmental Quality Historical Pollutant and Weather Data website front-page. (Source: TCEQHPWD, 2010).

Bureau of Reclamation

The Bureau of Reclamation operates a network of Hydromet sites along lakes and rivers throughout Texas. This website (see figure 27) provides graphical data for each selected site for measurements that include: daily mean gage height and height shift in feet; daily maximum, minimum and mean air temperature in degrees Fahrenheit; total precipitation and water year precipitation in inches; daily mean total discharge in cubic feet per second and daily mean, maximum and minimum water temperature in degrees Celsius. Some sites only have measurements pertaining to the river or lake and include precipitation. There are no numerical data available, only graphs; however, these graphs can be saved as an image.

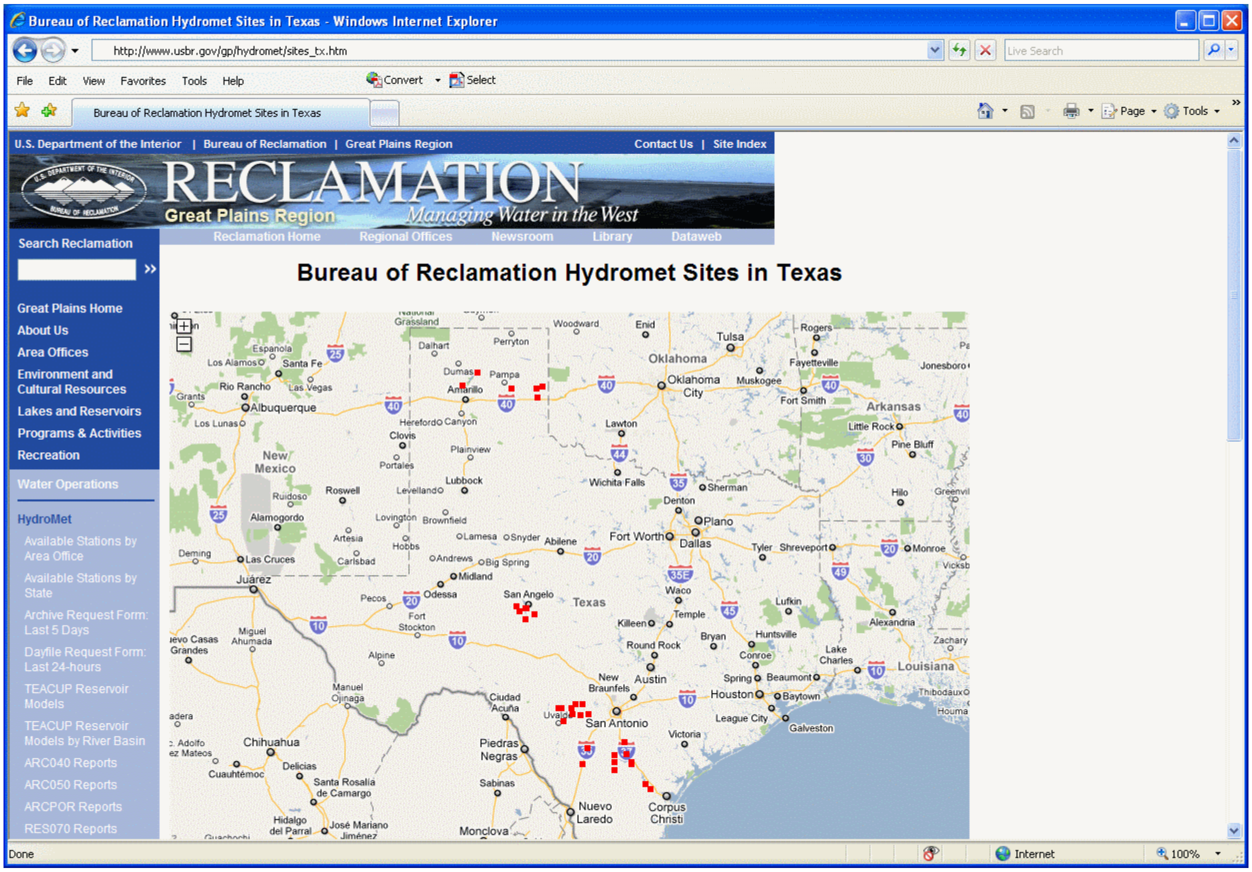


Figure 27. Bureau of Reclamation Network website front-page. (Source: BORHN, 2010).

WeatherBug

When this project was initiated, it was expected to find several “schoolnet” networks, however, only two were found. Upon further research it was learned that many more of these networks existed in the past but have since been taken over by WeatherBug. We found 12 television station networks that were taken over and include KFDM in Beaumont, KTSM in El Paso, KAUZ in Wichita Falls, WOAI in San Antonio, KPRC in Houston, KXAS in the Dallas-Ft. Worth area, KXTX in Dallas, KWTX in Waco, KXAN in Austin, KMOL in San Antonio, KLTV in Tyler and KAVU in Victoria. WeatherBug is a network (see figure 28) that monitors and displays weather data throughout the United States.

Figure 28. WeatherBug Network website front-page. (Source: WBN, 2010).

This network was not designed for agricultural use and does not make historical data available. The purpose of WeatherBug is to deliver live local weather conditions, forecasts and life saving severe weather alerts from its exclusive network of WeatherBug Tracking Stations. WeatherBug also has developed tools to assist educators, professionals and consumers understand and utilize weather information.

The measurements displayed by WeatherBug stations include current, high and low air temperature; heat index; relative humidity; rainfall; current and average wind speed, gust and directions; dew point temperature; barometric pressure and monthly accumulated rainfall.

Results

As expected, there exists a wide range of meteorological data from a variety of electronically accessible sources. Data exist in a variety of formats and are expressed in differing units. Details on sites and data values such as location parameters, sensor type and heights are typically not available.

A total of 25 data networks were researched and evaluated. Of these networks, 10 recorded the four necessary parameters required for ET calculation, six networks recorded three parameters (with solar radiation to be estimated) and eight networks were not viable for ET calculation (see table 1).

Some common issues among these networks include operations and maintenance support, funding for acquisition and processing, staffing (with retention and changeover concerns) and QA/QC procedures (for standardization). Several networks anticipated to be in service were no longer operational. These include the San Angelo Network (West Texas ET Network) and the Uvalde Precision Irrigators (PIN) Network. The San Angelo Network previously operated four stations. Upon retirement of the former network manager, the network was operated (without QA/QC or maintenance support) by county extension agents and secretarial staff for a few more months until it was decommissioned by default due to the lack of support funding.

Table 1. Assessment of Weather Station Networks' Viability for ET Applications.

Weather Station Networks with Data Suitable for ET Calculation	**Weather Station Networks useful for ET Calculation, but Requiring Estimated Solar Radiation**	**Weather Station Networks not Suitable for ET Calculation**
Texas ET Network	Iowa Environmental Mesonet	CoCoRAHS
Texas High Plains ET Network	KVII School Net	WeatherBug
Crop Weather Program	National Weather service	Bureau of Reclamation
West Texas Mesonet	National Climatic Data Center	iAIMS
MesoWest/ROMAN (selected sites)	Midsouth Weather Network	USDA Weekly Weather and Crop Bulletin
Desert Research Institute	KVIA Weathernet Lab	Lower Colorado River Authority
Weather Underground		Texas Coastal Ocean Observation Network
Texas AgriLife Center at Overton		Texas Commission on Environmental Quality
New Mexico Climate Center		US Historical Climatology Network

The Uvalde PIN Network originally operated 11 stations at Knippa, Sabinal, Uvalde St. John's, La Pryor, Crystal City, Carrizo Springs, Frio Town, the Texas A&M Uvalde Center, Concan, Batesville and Pearsall. After departure of a key scientist at the Uvalde center, the PIN Network was virtually dissolved until the Texas ET Network recently adopted nine of the original PIN network stations. The Uvalde Center and Concan stations do not collect new data and only offer historical data. The Batesville and Pearsall stations were taken offline completely and ceased operation.

Task 2

Site visitations, review discussions of sensors, acquisition parameters, and QA/QC procedures.

Methodology:

A survey was developed and conducted for available networks; of the survey addressed data acquisition and management, equipment used, network, technology transfer and other information (see table 2). The data acquisition and management category included type of data (meteorological, climate parameters), storing (archiving) of the data, frequency of data sequestration (seconds, minutes, hourly, daily), method of data sequestration (auto, manual), frequency of data output (matrix), interrogation interval, daily summary output, other data and units gathered. The data acquisition and management category also included data validity questions which included QA/QC methods, frequency, corrective methodology, the operating system (OS) system of the QA/QC programs (purchased or developed), data storage, backup frequency, operation (auto or manual), dissemination frequency (hourly or daily), whether ET is calculated, which ET equation(s)/methods are used, if calculations are conducted on board the datalogger or post processing and whether the original data are preserved and available. The equipment used category included types of sensors, data acquisition and other equipment, station site and sensor maintenance (regular routine), calibration (on-site vs. external), frequency, sensors used (type, model, height, orientation), lightening protection, sensory recalibration interval and stations power supply (self, auxiliary). The network category included the questions of how many and where the stations are located, site conditions (and area they represent), costs (sensors, hardware, calibration, etc.), costs (personnel, operations and maintenance - O&M), liability/warranty policy (certification), length of record, network support, annual costs of operation, annual costs of calibrations, staffing (number of employees), annualized programming costs, products available, cost of storage, media type and source of funding. The technology transfer category addressed the questions pertaining to data delivery, technology transfer (dissemination to public), who is using the data, for what purpose, target audiences and number of data users. The "other" category addressed other issues, target objectives, needs, problems, acknowledgement of cooperators, summary metrics and recommendations.

Table 2. ET Network Assessment Survey with Sample Responses.

Survey Questions with Sample Responses		
Category	**Question Item**	**Sample Responses**
Data	Type of data (meteorological, climate)	Various, depending upon network: Examples include maximum temperature, minimum temperature, relative humidity, wind speed and direction, barometric pressure, soil temperatures and heat units (calculated)
Data	QA/QC: methods, frequency, corrective methodology	Data limits, automated flags for manual (visual) inspection
Data	OS system of QA/QC programs… purchased or developed?	Developed by network staff
Data	Storing (archiving) data / Data Storage, backup frequency, operations (auto, manual)	Dedicated network computer, secured access only to room; mirrored servers, backed up every day; data analysis procedures
Data	Frequency of data sequestration (sec, min, hourly, daily)	Varies, (see interrogation interval and dissemination frequency items below)
Data	Method of data sequestration (auto, manual)	Automated (no manual) data downloads; phone, FTP, secured shell protocols implemented
Data	Interrogation interval	10 second, 1 minute interval, hourly averages (SR is cumulative) - interval depends on station (some are programmed by different people)
Data	Daily summary output?	(See Technology Transfer section)
Data	Data and units gathered - list	Data file name, columns pull-down menu, protocol; raw data goes to file, converted to other units; data exported to other database, then to website. 3 database minimum: raw data, clean data and calculated data
Data	Dissemination (output) frequency (hourly, daily)	Daily data are delivered; hourly can be downloaded (avg. temp, min RH,) hourly data stored in database
Data	Do you calculate ET?	Yes
Data	Which ET?	Standardized Penman-Monteith (probably the ASCE-EWRI), ETo (probably ETos)
Data	Calculations on board or post?	Some networks post calculated data; others post input data and host calculators on-line; calculated data sent through listserv
Data	Original data preserved?	Bad data omitted from "clean file" (kept in raw file), may just have missing data "NA"
Data	Other Comments	SQL database, QA/QC database - boundaries (temperature, etc.) "communication error" notification, error message indicates if data are out of bounds or if cell phone doesn't pick up, etc. Flags for visual inspection of data.

Data	Other Comments	Web site is outside the agency "grid"; network staff manually updates these computers, outside of normal agency operations
Equipment	Types of sensors, data acquisition and other equipment - (sensors, lightening protection)	Varies by network (see body of report)
Equipment	Station site and sensor maintenance? (regular routine?)	Varies by network (see body of report)
Equipment	Calibration (on-site vs. external), frequency	In-field rain gauge calibration; everything else is sent off for calibration by manufacturer
Equipment	Maintenance	Visual inspect 1/month; make sure pyranometer is not dirty, site inspection, (see handout)
Equipment	Sensor recalibration interval	Varies (annual is advocated)
Equipment	Stations power supply (self, auxiliary)	Varies by site, most are solar powered, some hardwired; remote location justifies solar power for many stations
Network	How many and where are the stations?	(see body of report)
Network	What are the site conditions (area they represent)	Golf courses, agricultural areas, turf areas. Recommend ASABE standard site conditions.. Some compromises, as necessary
Network	Costs - sensors, hardware, calibration…	Varies
Network	Costs - personnel, O&M	Some networks use agency staff (extra duties); part-time grant-supported positions; Cooperator/Sponsor based networks use in-kind labor contributions of cooperators. Staffing requirements: 1 or more manager (per network or station), plus computer/IT support, + technical support for instrumentation and site maintenance.
Network	Liability / warranty policy (certification)	"State uses it as best available"; no written disclaimer; TCEQ accepts it… no guarantee
Network	Length of record	Varies by site….. Up to 1994-1995….14 years; historic records up to 100 years from available data
Network	Network support	Agency personnel "extra duties" as assigned to network operations; grant-based or other "soft" funds are raised or diverted to maintain ET network operations. This is seen as a valuable contribution of service, though provided at significant cost for the providers.
Network	Annual costs of operation	Est. $100,000 plus staff time; plus cooperators' time; student workers, contract personnel are covered by external grant funding sources.
Network	Staffing (number of employees)	2+ staff members (full/part-time); cooperators
Network	Annualized programming costs	Varies; project-oriented and grant-funded
Network	Products available	See data section
Network	Cost of storage, media type?	Varies; project-oriented and grant-funded
Network	Sources of funding?	USDA-ARS Ogallala Aquifer Program funded projects; Texas Water Development Board funded development projects; Rio Grande Initiative (Task 2, education); short course revenues; Cotton Incorporated and other short-term commodity funded projects… All are soft funded; no agency "hard dollars" are provided.
Network	Number of stations	See body of report
Network	Area represented (acres)	See body of report
Network	Other comments	Weather reach; weather trac, smart irrigation controllers - get different ET calculations (probably *Hargreaves* equation);

Network	Other comments	Texas ET does not pay for phone lines…. Cooperators have to provide that. Only Texas ET owned stations are recalibrated at their expense. Cooperators have to pay their own.
Network	Other comments	Sponsorship fees charged for data QA/QC; tiers ($500, $1,000, $3,000) for levels of service
Technology Transfer	Data delivery	TexasET.tamu.edu website, software package… Texas landscape auditing software package; condensed version for homeowners, training manuals, Irrigation scheduler, CDs available through trainings (scheduler and auditing courses); manuals for training programs.
Technology Transfer	Technology transfer	Web sites
Technology Transfer	Who is using the data? For what?	Irrigation scheduling; environmental monitoring; TDA spray drift complaints; research programs; many others.
Technology Transfer	Target audiences	Landscape, ag irrigators, ag crop consultants; engineering consultants, city/municipalities, landscape licensed irrigators, homeowners, golf courses; irrigation districts; water districts; researchers; Sam Houston State, Tarrant County community College
Technology Transfer	Number of data users	15,000 website hits per month for each of the major networks (Texas ET and TXHPET)
Technology Transfer	Other comments	Use these numbers for the TCEQ On-site (long term ave. table)
Technology Transfer	Other comments	listserv - zip code or city; landscape or ag; e-mail weekly subscription either weekly weather summary and/or recommendation..weather data, calculator results …. Daily or weekly
Technology Transfer	Other comments	Overton station, Pemberton; Sponsored by East Texas irrigation association
Other Issues, Comments	Target objectives	Irrigation scheduling tool… promote irrigation through efficient irrigation scheduling…
Other Issues, Comments	Needs?	Money is a limiting factor (Note: this is an ongoing issue)
Other Issues, Comments	Problems?	Who is going to pay for it? New stations, phone, recalibrations, staffing…
Other Issues, Comments	Summary metrics	Website, listserv and other data requests are documentable; usage in research, outreach and other applications is more difficult to document, since many users do not cite or credit the source of the data.
Other Issues, Comments	Recommendations	Statewide network would require a full time coordinator with backup personnel, plus field staff
Other Issues, Comments	Estimating funding requirements	Estimated costs of network operations (reported elsewhere)
Other Issues, Comments	Acknowledge cooperators & TWDB for funding, grant	Acknowledgement of cooperators, funding sources, etc. is very important to interviewees as well as to the project team.

It should be noted for the record that this project task was awarded and approved with sufficient travel budget for visits to many, if not all, of the respective ET networks and non-network sites and to meet individually for detailed discussion with the network managers identified in task 1. However, significant difficulties were experienced between the accounting and legal departments of the respective state agencies over accounting records, expense issues and specific and detailed submission formats. This was the case even after several in-person meetings between various contract personnel of the two agencies. Thus, reimbursement of travel expenses for project personnel was in question for much, if not all, of the contract period and the project team faced ongoing reimbursement uncertainty. To limit the resultant personal out of pocket expense liability, the project team limited or suspended travel, leaving much of the project travel budget unused. Alternate acquisition methods (that were less complete) were developed and implemented by the PI's to gather as much of the proposed data as possible from the respective networks in lieu of on-site discussions. These alternative methods included discussion with network managers at other related professional and scientific conferences and meetings during the course of the project task. Additionally, extensive web based interrogation of the networks sites was conducted with attempted follow-up phone conversation or emails with managers or operational personnel.

Results

Network discussions were individually held with personnel of the TXHPET Network, the Texas ET Network and the default manager of the Precision Irrigators Network regarding all parameters of interest for this task. Other ET network managers were contacted but declined participation in the project survey. Multiple conversations and meetings were held with Mr. Charles Swanson of the Texas ET Network. The PIN Network is now part of the Texas ET Network. The St. Lawrence Region network (the West Texas ET Network) ceased maintenance in August 2008 with the retirement of Dr. Billy Warrick and with subsequent relocation of Texas AgriLife Integrated Pest Management agents maintaining the stations. We visited with managers of other state networks at other venues (WERA-202 project meetings, ASCE-EWRI and ET Task

Committee meetings and ASABE conferences). Travel expenses of these meetings were not charged to this grant, but were made possible by other grant sources. Where possible, information was acquired through telephone conversations, e-mail communications and website interrogation.

For the TXHPET Network, the typical measurements acquired include air temperature, relative humidity, wind speed and direction, solar radiation, precipitation, soil temperature at 5 and 15 cm (2 and 6 in.), actual vapor pressure, vapor pressure deficit, standard deviation of wind direction and barometric pressure. The TXHPET QA/QC procedures include automated acquisition of all data parameters as well as battery voltages and datalogger temperature. Upload of the data and subsequent calculations (ETref, heat units, crop growth models, etc.) to the on-line database have been automated. Data are subsequently visually and graphically inspected by a qualified and highly experienced research associate (RA) every 7 to 10 days. The inspection identifies graphical and numeric follow-up data anomalies (out of range values, trends that may indicate sensor drift or problems) and corrections are made as necessary. All original, raw data values are retained as logged at the field sites. When a problem is identified by custom programmed data scanning scripts, an automated message is sent to the QA/QC RA who then informs the project managers who ensure the problem is corrected. Other technical personnel on occasion may be required for corrective action depending on the severity or complexity of the issue. Typical fault issues are caused by problems with phone lines, hail, floods, vandalism, theft, bird damage, rodents, lightning, horses and rogue cattle (destroying an entire station). The least common malfunction has been instrumentation failure, particularly when routine maintenance is practiced.

The Texas ET Network measurements include air temperature, relative humidity, solar radiation, rainfall and wind speed. Regarding QA/QC, the Texas ET Network cooperators agree to maintain station equipment according to network recommended schedules. Cooperators are asked to submit forms verifying maintenance schedules. The QA/QC database contains boundaries, upper and lower limits for data parameters. There are also communication error notifications. Error messages indicate if data are out of bounds or if cell phone modems fail to properly connect for transmission. Flags are used on the website to indicate the need for visual inspection of data.

The Crop Weather Program (CWP) at Corpus Christi is managed by Dr. Carlos Fernandez of Texas AgriLife Research. There is some overlap in territory and station locations with the Texas ET Network. Though information delivery is different from the Texas ET Network, the CWP station network model is very similar. Stations are maintained by cooperators, generally county extension agents, cotton gin personnel, agricultural producers, etc. The CWP measurements include air temperature, relative humidity, solar radiation, wind speed and direction, soil temperature at the 2.54, 7.6 and 30.5 cm (1, 3 and 12 in.) depths and precipitation. The weather data are automatically collected over land-lines and wireless networks several times daily. Data are checked for common errors (out-of-range sensor values, data recording anomalies) and cross checked against other weather stations. Access to these data requires a user account/login.

The iAIMS climatic data site is operated by the Texas AgriLife Research Center at Beaumont. They have varying weather data sources which include NOAA, National Climatic Data Center, COOP stations, Meteorological Aviation Report (METAR), CWP weather station network at Corpus Christi and Beaumont/Eagle Lake research weather stations. This network includes no operation and maintenance as it is a source of data acquisition and transfer only. A linear interpolation method is used to estimate 10 or fewer consecutive missing data points for air temperature, relative humidity, wind speed, wind direction, solar radiation and ETref. Historic average weather data are used and adjusted for longer periods of missing data. This network automatically acquires and uploads data to the iAIMS database. NOAA weather data are delayed one to two months whereas local sources are available after one to three days. NOAA site data parameters vary with location but most offer only maximum and minimum air temperature plus precipitation.

The San Angelo Network has been “decommissioned by default” since this project was initiated. The Uvalde PIN Network also had fallen into disrepair due to the lack of funding and skilled/dedicated expertise between the time of initiation of this project and recent months resulting from personnel changes in Texas AgriLife Research. Due to popular demand by end-users and with some funding support from the Texas Water Resources Institute (TWRI), several of the stations have been adopted by the Texas ET Network. Operations, maintenance and QA/QC will adhere to the Texas ET Network model.

MesoWest is a network run by The University of Utah. It was designed for use by National Weather Service meteorologists and other professionals for protection of life and property. QA/QC is applied to the data as they are processed. This includes range checks for all variables and statistical checks for air temperature, relative humidity and barometric pressure. MesoWest statistical checks include comparison of the linear regression estimates of parameters to the observed data (see figure 29). The QA/QC data flags are indicated by color on the website. Black values mean the data have passed all QC checks. Orange values mean caution as some data have been flagged by the statistical check and should be used with caution. Red values indicate suspect data as some data have been found to be outside reasonable bounds. The data are still displayed, even those they failed QA/QC protocols, and are marked as "use at your own risk."

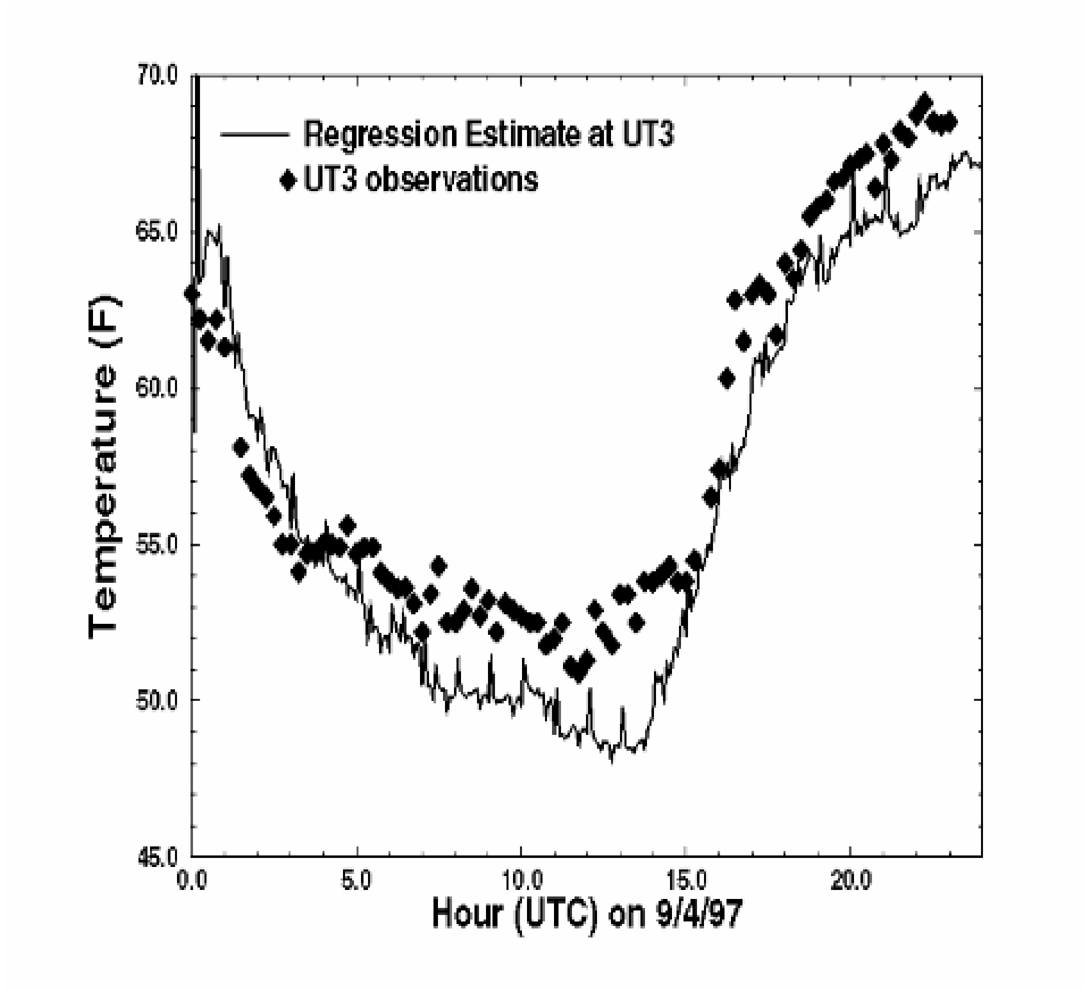
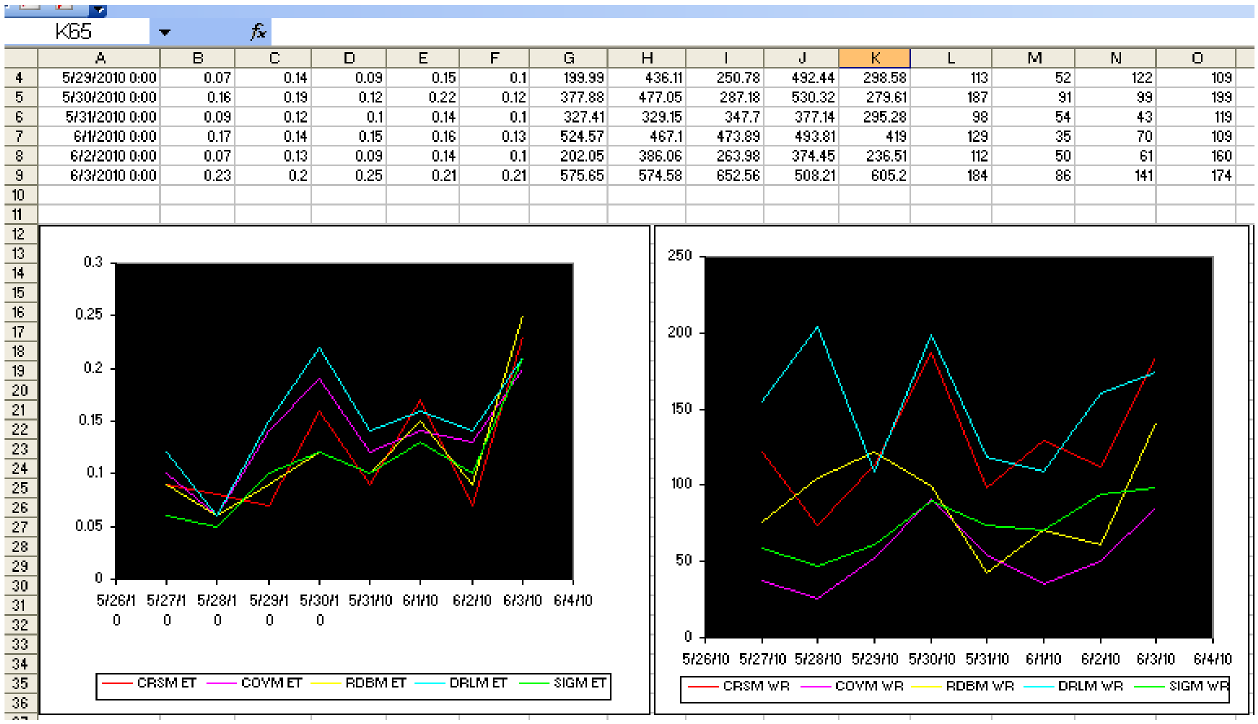


Figure 29. Statistical regression value estimation plot of MesoWest station data versus observations to detect errors. (Source: MesoWest, 2010).

Table 3. MesoWest Maximum and Minimum Data Flagging Criteria. (Source: MesoWest, 2010).

Variable	Minimum Value	Maximum Value
Pressure (mb)	600	1049
Temperature (^{o}F)	-75	135
Dew Point (^{o}F)	-75	135
Relative Humidity (%)	0	100
Wind Speed (knots)	0	125
Wind Direction (degrees)	0	360

Some networks located outside the state of Texas were researched to find available QA/QC procedures, but were not listed in task 1 due to the fact that they are not usable for ET calculation within the state. These networks apply a wide array of QA/QC procedures and methods and include the AgriMet network, which covers the Northwestern U.S. and is managed by Peter Palmer. This network has developed a MS® Visual Basic/MS Excel spreadsheet program to generate easy to inspect, graphical summaries of data for visual inspection (see figure 30). Another data network is the NOAA Meteorological Assimilation Data Ingest System (MADIS). This system uses a validity of data range method which checks for internal, temporal, spatial and statistical consistency.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
4	5/29/2010 0:00	0.07	0.14	0.09	0.15	0.1	199.99	436.11	250.78	492.44	298.58	113	52	122	109
5	5/30/2010 0:00	0.16	0.19	0.12	0.22	0.12	377.88	477.05	287.18	530.32	279.61	187	91	99	199
6	5/31/2010 0:00	0.09	0.12	0.1	0.14	0.1	327.41	329.15	347.7	377.14	295.28	98	54	43	119
7	6/1/2010 0:00	0.17	0.14	0.15	0.16	0.13	524.57	467.1	473.89	493.81	419	129	35	70	109
8	6/2/2010 0:00	0.07	0.13	0.09	0.14	0.1	202.05	386.06	263.98	374.45	236.51	112	50	61	160
9	6/3/2010 0:00	0.23	0.2	0.25	0.21	0.21	575.65	574.58	652.56	508.21	605.2	184	86	141	174

Figure 30. AgriMet graphical comparisons of similar station groupings and of parameters for error detection. (Source: AgriMet, 2010).

The Oklahoma Mesonet's standard primary variables (measured at every site) include air temperature at a 1.5 m (5 ft) height, relative humidity at a 1.5 m (5 ft) height, wind speed and direction at a 10 m (33 ft) height, barometric pressure, rainfall, incoming solar radiation and soil temperature at the 10 cm (4 in.) depth under natural sod cover and bare soil. Other measurements taken at some, but not all, sites include air temperature at a 9 m (29.5 ft) height, wind speed at a 2 and 9 m (6.6 and 29.5 ft) heights, soil moisture at the 5, 25, and 60 cm (2, 9.8 and 23.6 in.) depths, soil temperature at the 5 and 30 cm (2 and 11.8 in.) depths under natural sod cover and soil temperature at the 5 cm (2 in.) depth under bare ground. The QA/QC procedures for this network include a combination of laboratory calibration, on-site inter-comparison, automated QA and manual QA. All sensors are calibrated in the laboratory to validate or improve upon factory calibrations. Field sensors are compared annually with portable calibrated sensors. Automated QA software includes numerous algorithms to evaluate all data received from remote stations. Meteorologists use manual techniques to complement the automated QA. Analysis also is performed using monthly statistics to detect sensor drift or instrumentation bias. Meteorologists then communicate errors to field technicians to correct any detected problems or errors.

The most common concerns for most of these networks are funding stability, staffing issues, sensor accuracy and maintenance, telecommunications reliability, data QA/QC, data management, delivery management, standardization (siting, data units, quality etc.) and the need for education to support appropriate applications plus interpretation of the data.

Summary

Several ET networks were assessed through discussions with available managers, and it was found that varying methods of parameter measurement, ET calculations and QA/QC are being used. It was found that the majority of networks is operated by or is associated with universities or other scientific agencies. Some of the programs have either been terminated or have experienced operations problems due to fiscal constraints or changing agency personnel and priorities.

The QA/QC procedures implemented by the respective networks vary throughout the state. It is recommended that a minimal set of procedures be implemented particularly regarding temperature and solar radiation values. Maximum and minimum air temperature measurements should be compared against long term average maximum and minimum values and adjusted accordingly if substantial deviations are detected in the data. Similarly, cumulative daily solar radiation values should be compared against long term maximum clear day sky radiation values and adjusted accordingly. Adjustments should only be made if ancillary data parameters support them. Recommended QA/QC procedures and guidelines include FAO-56 (Allen et al., 1998), the ASCE-EWRI Standardization of Reference ET (Allen et al., 2005), ASCE-EWRI memo on Quality Assessment and Control of Automated Weather Data (ASCE, 2009) and the ASABE Engineering Practice 505 (ASAE, 2004). Procedures of these guidelines are cited in the references section. These references entail nearly 1,000 pages of documentation and the reader is encouraged to research or review these for specific processes regarding QA/QC guidelines and maintenance actions. There is also a very extensive document on guidelines and recommendations available from the World Meteorological Organization principally pertaining to climatology based applications.

Task 3

Sensitivity Analysis of Network Based Parameter Data

Methodology

Archived climate data for the period of 1991 to 2008 from the TXHPET (USDA-ARS) weather station located at Bushland, Texas were used in this sensitivity analysis. Reference ET (ETref) values were calculated using the ASCE Standardized ET Equation for grass and alfalfa references (see Allen et al., 2005). The ETref values were calculated for hourly intervals and summed to provide a daily value. Once the base reference ET's were known, one climate parameter at a time was modified while keeping all other parameters constant to determine the effect of that parameter on the ETref values. This was done individually for five climate parameters of air temperature, wind speed, solar radiation, relative humidity and dew point temperature. The hourly air temperature and dew point temperatures were altered at 2 ^{o}C intervals from -6 to +6 ^{o}C (3.6 to 10.8 ^{o}F, respectively). These new values were then used to calculate grass and alfalfa reference ET. Similarly, hourly wind speed was altered at 2 m/s intervals from -6 to +6 m/s (4.47 to 13.42 mph). Hourly solar radiation was altered plus and minus 25, 50 and 75 W m^{-2} (out of a typical maximum value of 1100 W m^{-2}). Hourly relative humidity was altered plus and minus 10, 20 and 30 percent. When the relative humidity exceeded 100 percent, a value of 100 was used. This provided the effect each parameter has on reference ET individually. Once this was completed for each parameter individually, the impact of two parameters adjusted simultaneously was evaluated. To do this, hourly wind speed was elevated by 2 m/s and the hourly air temperature was altered at 2 ^{o}C intervals from -6 to +6 ^{o}C (-10.8 to +10.8 ^{o}F). This procedure was repeated with the -2 m/s wind speed. This provided the combination effect of sensor errors with 2 parameters varying on the ETref computation.

Knowing these effects provides an indication of the accuracy need of data and of properly maintained and calibrated sensors.

To determine which climate parameter was the most sensitive, a sensitivity coefficient (Cs) (Irmak et al., 2006) was calculated. The Cs for each climate variable was calculated by dividing the amount of change in reference grass or alfalfa based ET by a unit change (25 W m^{-2} for solar radiation and 1 unit increase or decrease for all other variables) in each climate parameter on a daily basis. Finally, sensitivity coefficients for all climate parameters were compared to determine sensitivity of each parameter over different cropping seasons. The higher the Cs value for a climate parameter, the more sensitive the ET calculation is to changes regarding that parameter(s).

(The reader should recognize that while ETos and ETrs differ in value with respect to the ETref computations, crop ET (ETc) is the same and thus the respective crop coefficients are different for a grass and alfalfa ET reference.)

Results

Figure 31 illustrates change in ETos and ETrs due to change in air temperature individually while values of all other climate parameters were kept constant. A 2 ^{o}C (3.6 ^{o}F) increase in air temperature increased the daily grass reference ET (ETos) and alfalfa reference ET (ETrs) by 0.5 mm (0.02 in.) and 0.75 mm (0.03 in.), respectively. The relationship is linear for the ETos, however, it is slightly non-linear when air temperature decreases as illustrated in figure 31 for ETrs. Similar trends were found with -2,-4,-6, +4, and +6 ^{o}C variants. For example, a 4 ^{o}C (+7.2 ^{o}F) increase in air temperature increased daily ETos by 1.0 mm (0.04 in.); however, a 4 ^{o}C (-7.2 ^{o}F) decrease in air temperature caused a 0.9 mm (0.035 in.) reduction in ETos. In the case of

ETrs, a 2, 4 and 6 ^{o}C increase in air temperature caused a 0.75 mm (0.03 in.), 1.6 mm (0.063 in.), and 2.4 mm (0.094 in.) increase, respectively. Decreasing air temperature by 2, 4, and 6 ^{o}C decreased ETrs by 0.75 mm (0.03 in.), 0.4 mm (0.055 in.) and 2 mm (0.079 in.), respectively.

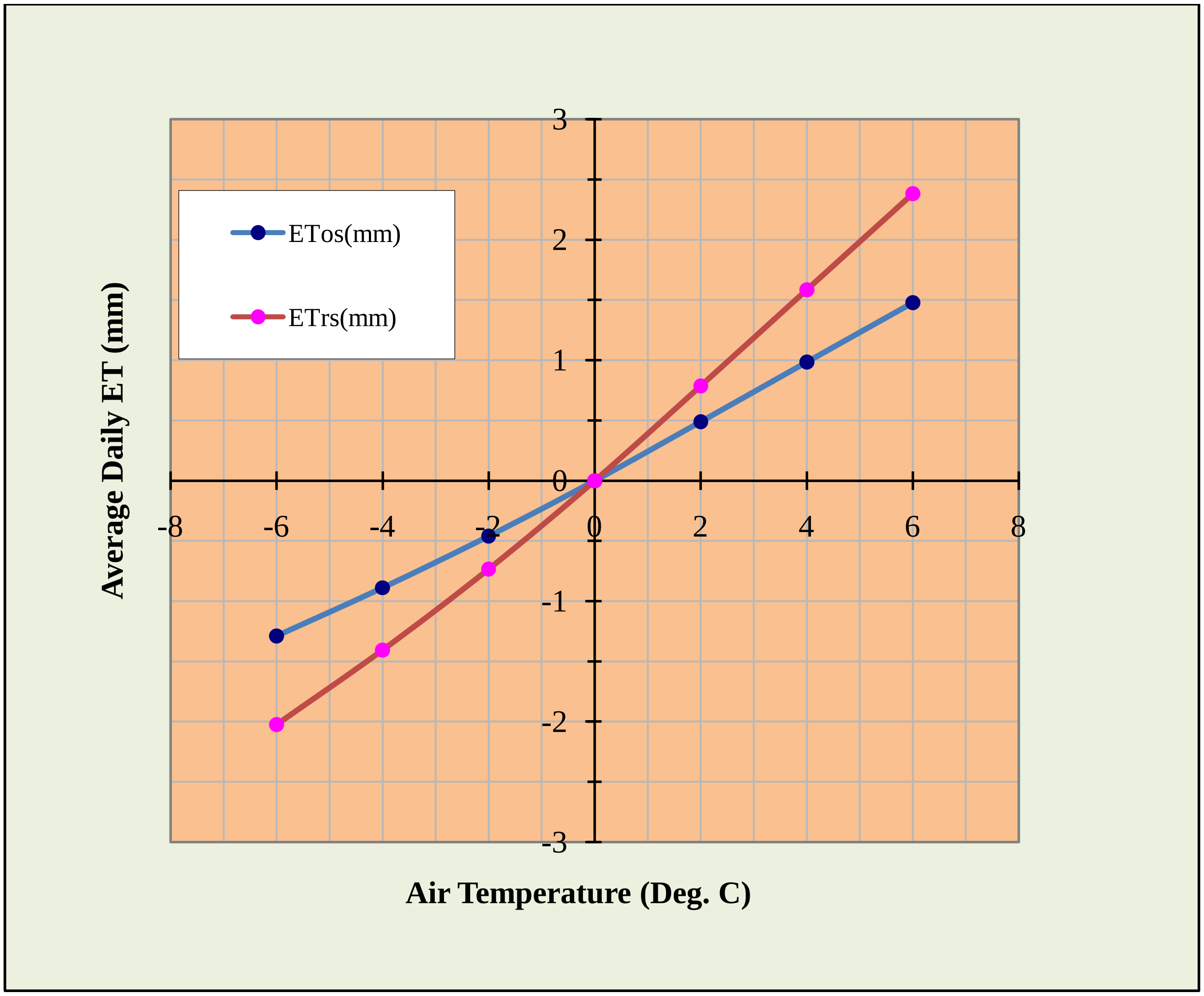


Figure 31. Effect of increase or decrease in hourly air temperature on daily grass and alfalfa reference ET.

For the wind speed variants (see figure 32), neither the ETos or ETrs relationships were linear. An increase in wind speed by 2 m/s (4.47 mph) elevated the ETos by 0.5 mm (0.02 in.). A decrease in ETos by the same amount was obtained when wind speed was reduced by 2 m/s.

Similar trend was found with wind speed intervals of +4, +6, -4 and -6 m/s. For ETrs, the changes are more drastic. A 2 m/s (4.47 mph) increase in wind speed caused an increase in ETrs of 0.8 mm (0.031 in.). This is about 60 percent higher than that for ETos for a similar change of 2 m/s. Increasing wind speed by 4 m/s (8.95 mph) will cause a 1.5 mm (0.059 in.) increase in ETrs and a 6 m/s (13.42 mph) increase in wind speed will increase ETrs by 2 mm (0.079 in.). Conversely, decreasing wind speed by 2 m/s (4.47 mph) will decrease ETrs by 1 mm (0.039 in.). A 4 m/s (8.95 mph) reduction in wind speed will reduce ETrs by 1.9 mm (0.075 in.) and a 6 m/s (13.42 mph) reduction in wind speed will decrease ETrs to 2.4 mm (0.094 in.).

Figure 33 illustrates the effect of changes in hourly dew point temperature on daily ETos and ETrs. It can be clearly seen that there is an inverse relationship between dew point temperature and reference ET. This was expected as an increase in dew point temperature is an indicator of more moisture in the air and therefore less ET demand. Increasing dew point temperature by 2 ^{o}C (3.6 ^{o}F) will decrease ETos by 0.4 mm (0.016 in. - see figure 33).

An increase of 4 ^{o}C (7.2 ^{o}F), and 6 ^{o}C (10.8 ^{o}F) decreased ETos by 0.2 mm (0.016 in.), 0.5 mm (0.02 in.), and 0.7 mm (0.028 in.), respectively. Similar trend was found in the opposite direction when dew point temperature was decreased by 2, 4, and 6 ^{o}C (3.6, 7.2 and 10.8 ^{o}F). Trends in ETrs were similar to those in ETos when the dew point temperature was increased or decreased, however, at a slightly higher magnitude. For example, an increase of 2 ^{o}C (3.6 ^{o}F) in dew point temperature lowered ETrs by 0.4 mm (0.016 in.). This is about 100 percent decrease when compared to change in ETos for a similar change in dew point temperature. This clearly indicates that ETrs is more sensitive than ETos to changes in the climate parameters.

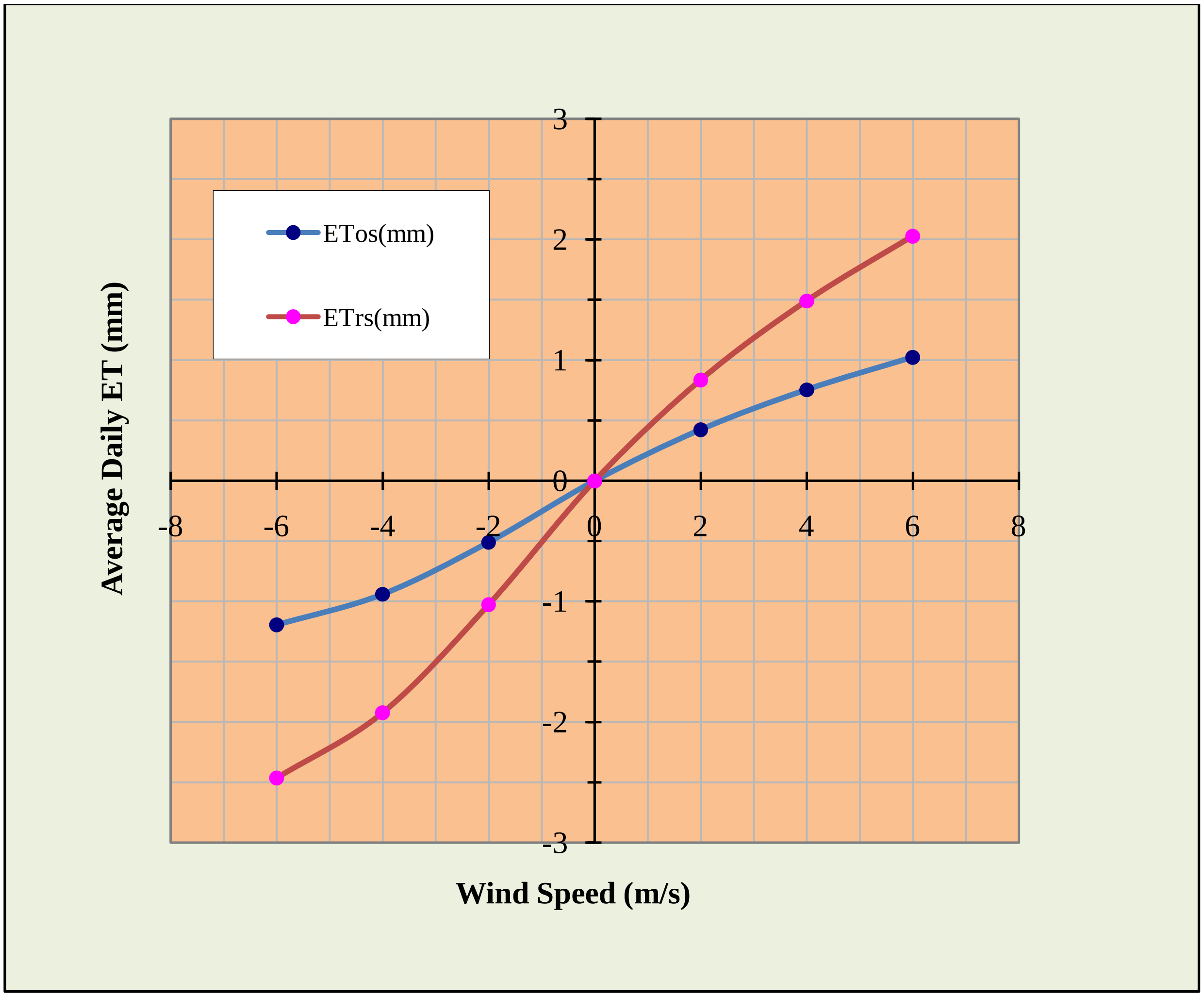


Figure 32. Effect of decrease or increase in hourly wind speed on daily grass and alfalfa reference ET.

Figure 34 illustrates the effect of changes in hourly solar radiation on daily ETos and ETrs. Comparison of changes in ETos and ETrs to changes in solar radiation is much smaller than that for air temperature, wind speed, and dew point temperature. Also, differences between ETos and ETrs are much smaller. Increasing radiation by 25 W m^{-2} raised ETos by 0.25 mm (0.0098 in.) and ETrs by 0.3 mm (0.012 in.). Increasing radiation by W m^{-2} raised ETos by 0.4 mm (0.016 in.) and ETrs by 0.5 mm (0.02 in.). Increasing radiation by 75 W m^{-2} increased ETos by 0.6 mm

(0.024 in.) and ETrs by 0.7 mm (0.028 in.). The ETos and ETrs were decreased by similar amounts when solar radiation was decreased.

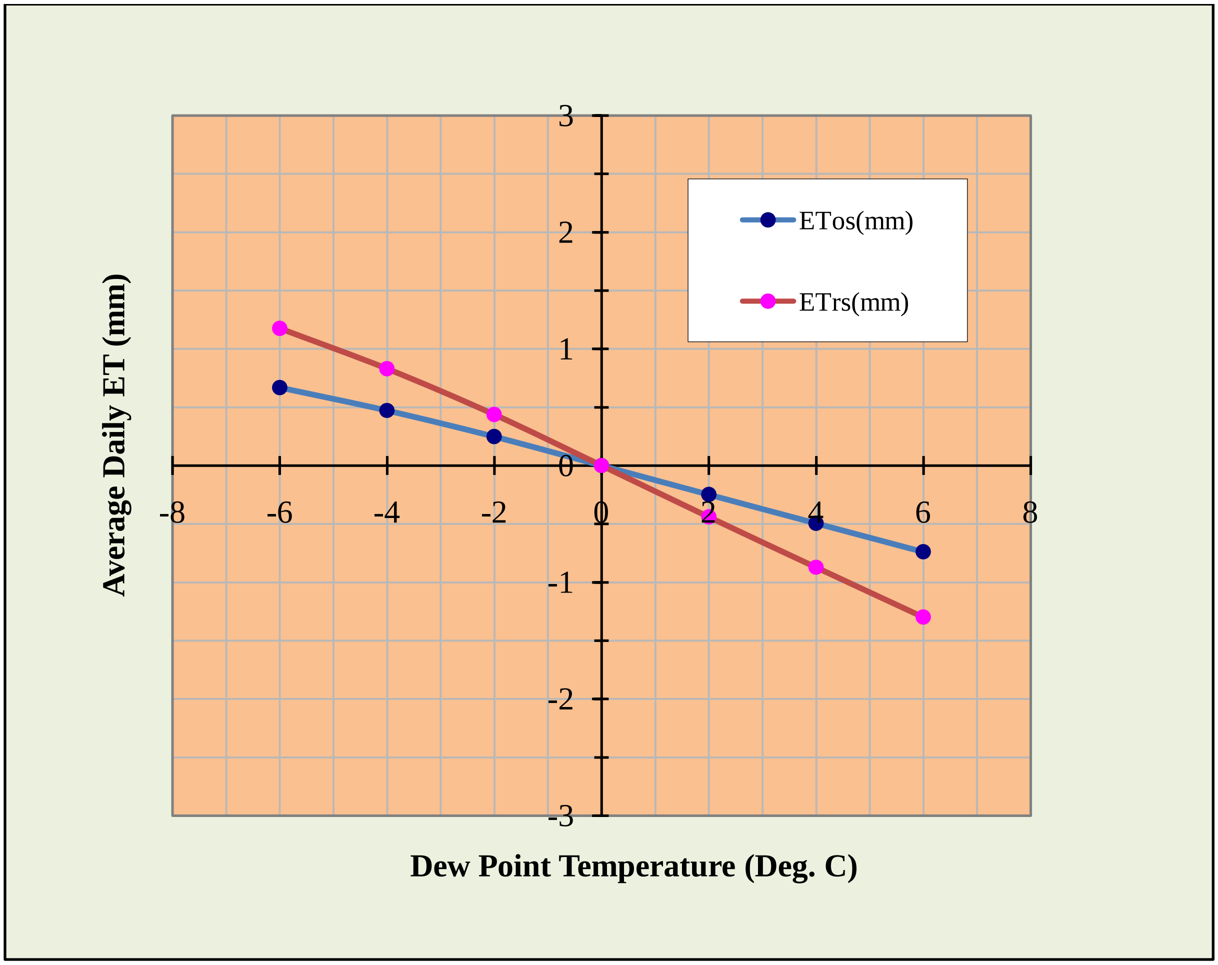


Figure 33. Effect of decrease or increase in hourly dew point temperature on daily grass and alfalfa reference ET.

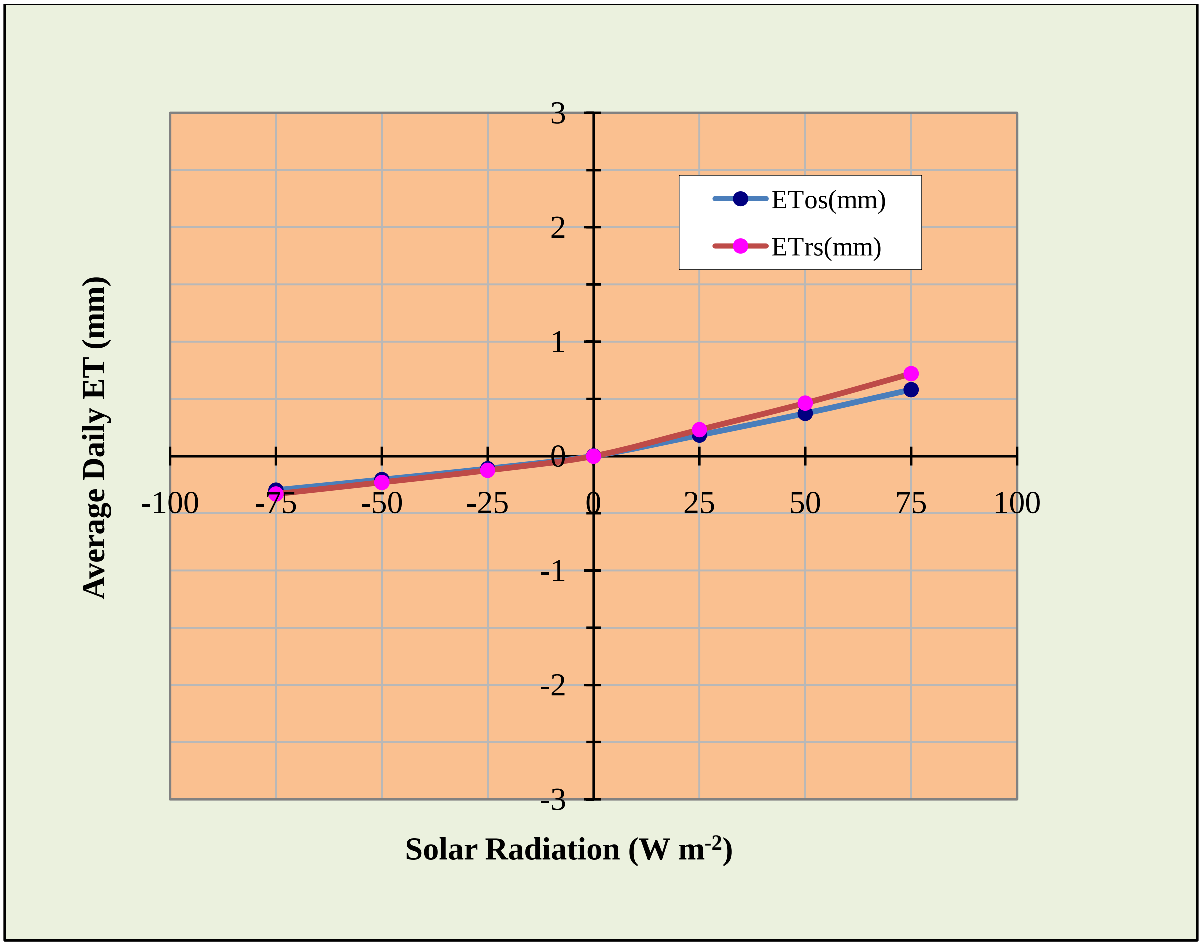


Figure 34. Effect of decrease or increase in hourly solar radiation on daily grass and alfalfa reference ET.

Figure 35 illustrates combination changes in ETos as a result of changes in the hourly air temperature at -2 0, and +2 m/s wind speed increments. At a wind speed increment of 2 m/s (4.47 mph), an increment in the air temperature by 2 ^{o}C increased the daily ETos from 0.5 mm (0.0197 in.) to 1 mm (0.039 in.). This is a 100% increase in the ETos estimation. However, the daily ETos was reduced from 0.5 mm to -0.19 mm when the air temperature and wind speed were reduced by 2 ^{o}C and 2 m/s, respectively. Reducing wind speed and leaving the air temperature value unchanged lowers daily ETos by 0.5 mm (0.02 in.). Lowering air temperature by 2 ^{o}C (3.6 ^{o}F), with the 2 m/s (4.47 mph) decrease in wind speed, caused a reduction of 0.8 mm (0.031 in.) in ETos. Decreasing air temperature by 4 ^{o}C (7.2 ^{o}F) with the reduction in wind speed lowers ETos by 1.2 mm (0.047 in.). Decreasing air temperature by 6 ^{o}C (10.8 ^{o}F), with the reduction in wind speed, lowers ETos by 1.4 mm (0.055 in.). When wind speed is increased by 2 m/s (4.47 mph) and air temperature is elevated by 2 ^{o}C (3.6 ^{o}F), ETos increased by 1 mm (0.039 in.). Raising air temperature by 4 ^{o}C (7.2 ^{o}F), with a 2 m/s (4.47 mph) increase in wind speed, caused an increase in ETos of 1.7 mm (0.067 in.) per day. An increase of 6^{o} C (10.8^{o} F) in air temperature, coupled with the 2 m/s (4.47 mph) increase in wind speed, raised ETos by 2.4 mm (0.094 in.). Increasing wind speed by 2 m/s (4.47 mph) and leaving air temperature unchanged increased ETos by 0.5 mm (0.02 in.). Decreasing air temperature by 2 ^{o}C (3.6 ^{o}F), with the increase of 2 m/s (4.47 mph) in wind speed lowered the ETos by 0.1 mm (0.0039 in.). Decreasing air temperature by 4 ^{o}C (7.2 ^{o}F), coupled with the increase in wind speed lowered ETos by 0.7 mm (0.028 in.). A reduction in air temperature by 6 ^{o}C (10.8 ^{o}F), with the 2 m/s (4.47 mph) increase in wind speed causes ETos to be reduced by 1.2 mm (0.047 in.). When plotted (see figure 35), the three curves for air temperature, one each with increased and decreased wind speeds by 2 m/s and one with the base data wind speed, all converge to a single point when air temperature is decreased. This convergence point occurs around a drop in daily ET of 1.5 mm (0.059 in.). Overall, changes in ETos were exponential with simultaneous changes in air temperature and wind speed.

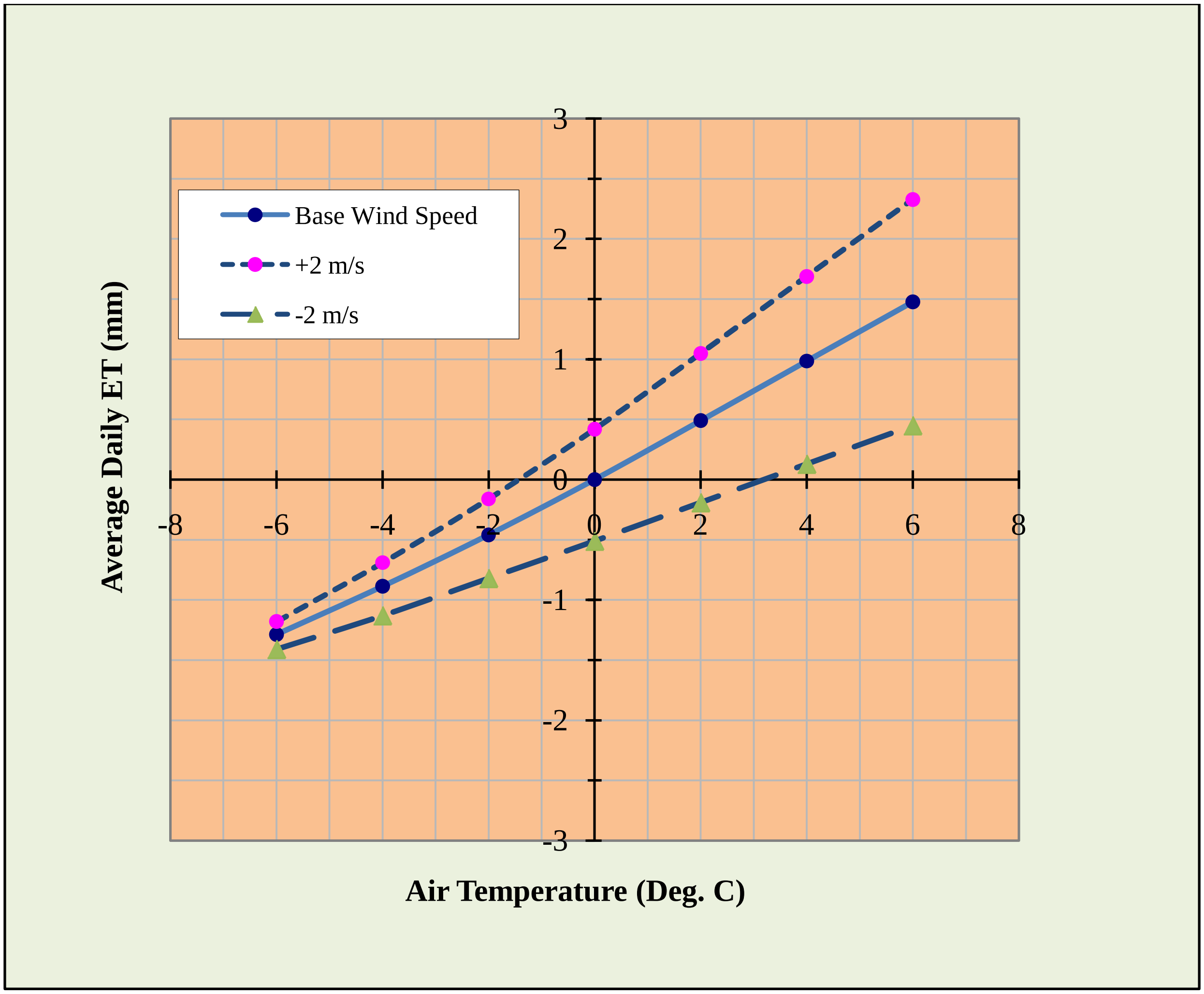


Figure 35. Effect of simultaneous change in both wind speed and air temperature on daily grass reference ET.

Similar trends as in ETos were found with ETrs but at slightly higher magnitude when air temperature and wind speed were changed simultaneously (see figure 36). Reducing wind speed by 2 m/s (4.47 mph) and increasing air temperature by 2 ^{o}C (3.6 ^{o}F) lowered estimated ETrs by 0.5 mm (0.02 in.) per day. Increasing in air temperature by 4 ^{o}C (7.2 ^{o}F) coupled with the reduction in wind speed, the ETrs stayed the same as the base value. Increasing air temperature by 6 ^{o}C (10.8 ^{o}F), with the reduction in wind speed, increased ETrs by 0.5 mm (0.02 in.).

Reducing only the wind speed by 2 m/s (4.47 mph) and leaving the air temperature value unchanged lowered the ETrs by 1 mm (0.039 in.). Reducing both the wind speed by 2 m/s (4.47 mph) and the air temperature by 2 ^oC (3.6 ^oF) reduced ETrs by 1.5 mm (0.059 in.). Reducing air temperature by 4 ^oC (7.2 ^oF), with the reduction in wind speed, lowered ETrs by 2 mm (0.079 in.). A reduction of 6 ^oC (10.8 ^oF) in air temperature coupled with the reduction in wind speed reduced estimated daily ETrs by 2.4 mm (0.094 in.). Raising air temperature by 2 ^oC (3.6 ^oF) and wind speed by 2 m/s, caused an increase of 1.9 mm (0.075 in.) in ETrs. Raising air temperature by 4 ^oC (7.2 ^oF), and increasing wind speed by 2 m/s, increased ETrs by 2.9 mm (0.11 in.). Increasing air temperature by 6 ^oC (10.8 ^oF), with an increase in wind speed, increases ETrs by 4 mm (0.16 in.). Increasing the wind speed by 2 m/s (4.47 mph) and leaving air temperature unchanged increased ETrs by 0.8 mm (0.031 in.) per day. Reducing air temperature by 2 ^oC (3.6 ^oF) and increasing wind speed lowered ETrs by only 0.1 mm (0.0039 in.). Decreasing air temperature by 4 ^oC (7.2 ^oF), with the increase in wind speed, decreased ETrs by 1 mm (0.039 in.). Decreasing air temperature by 6 ^oC (10.8 ^oF), coupled with the increase in wind speed, will decrease ETrs by 1.7 mm (0.067 in.). When plotted (see figure 36), the curves for ETrs with 2 variables changed also converge to a single point. This convergence point happens when ETrs is reduced by 2.5 or 3 mm (0.098 or 0.12 in.).

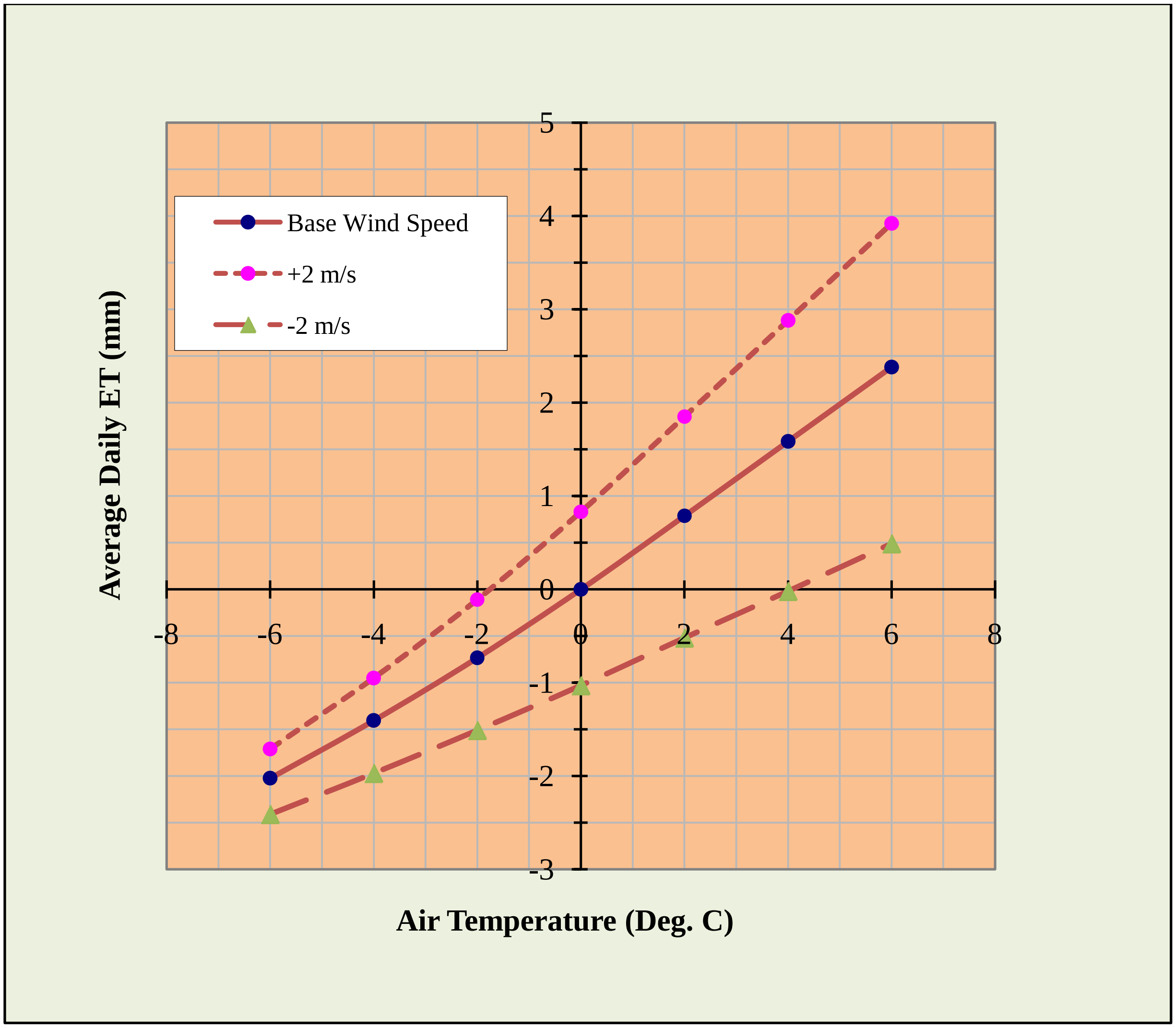


Figure 36. Effects of simultaneous changes in both wind speed and air temperature on daily alfalfa referenced ET.

Figure 37 and figure 38 illustrate the parameter sensitivity of ETos and ETrs to variations in air temperature, wind speed, dew point temperature, and solar radiation. It can be observed that individual parameters do significantly affect ET calculations. As illustrated, the sensitivity to the data parameters is dramatically increased during the summer growing season period. Wind speed is found to be the most impacting parameter followed by air temperature. However, solar radiation errors during the mid-summer growing period also play a significant impacting role in affecting ET computations. These sensitivity effects are expected to be compounded when 2 or more variables are altered.

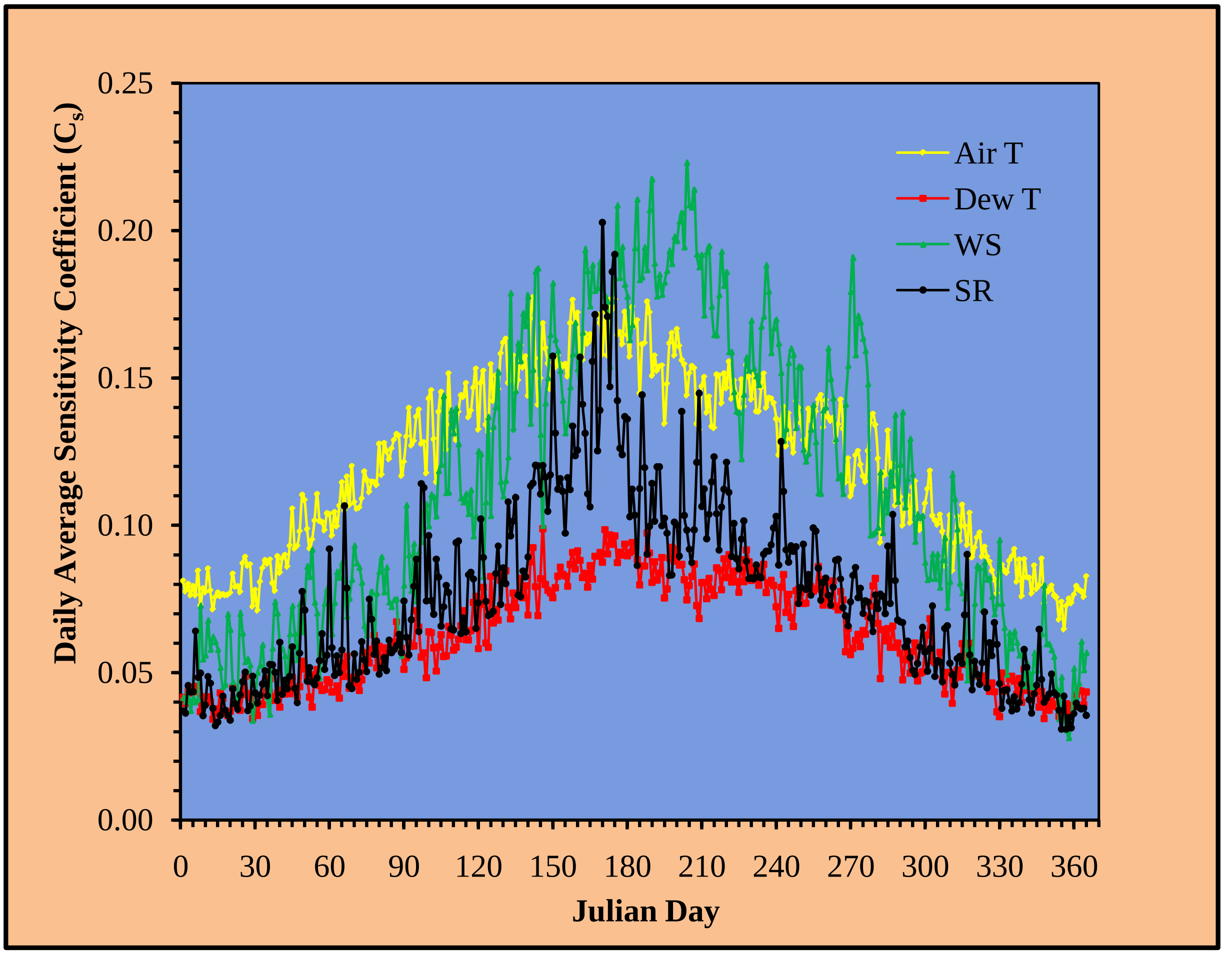


Figure 37. Daily average ETos sensitivity coefficients for air temperature, dew point temperature, wind speed and solar radiation.

The impact of this task analysis and the associated deviations may seem complex and abstract. However, when these effects are applied to regional scale crop water demand estimates, their

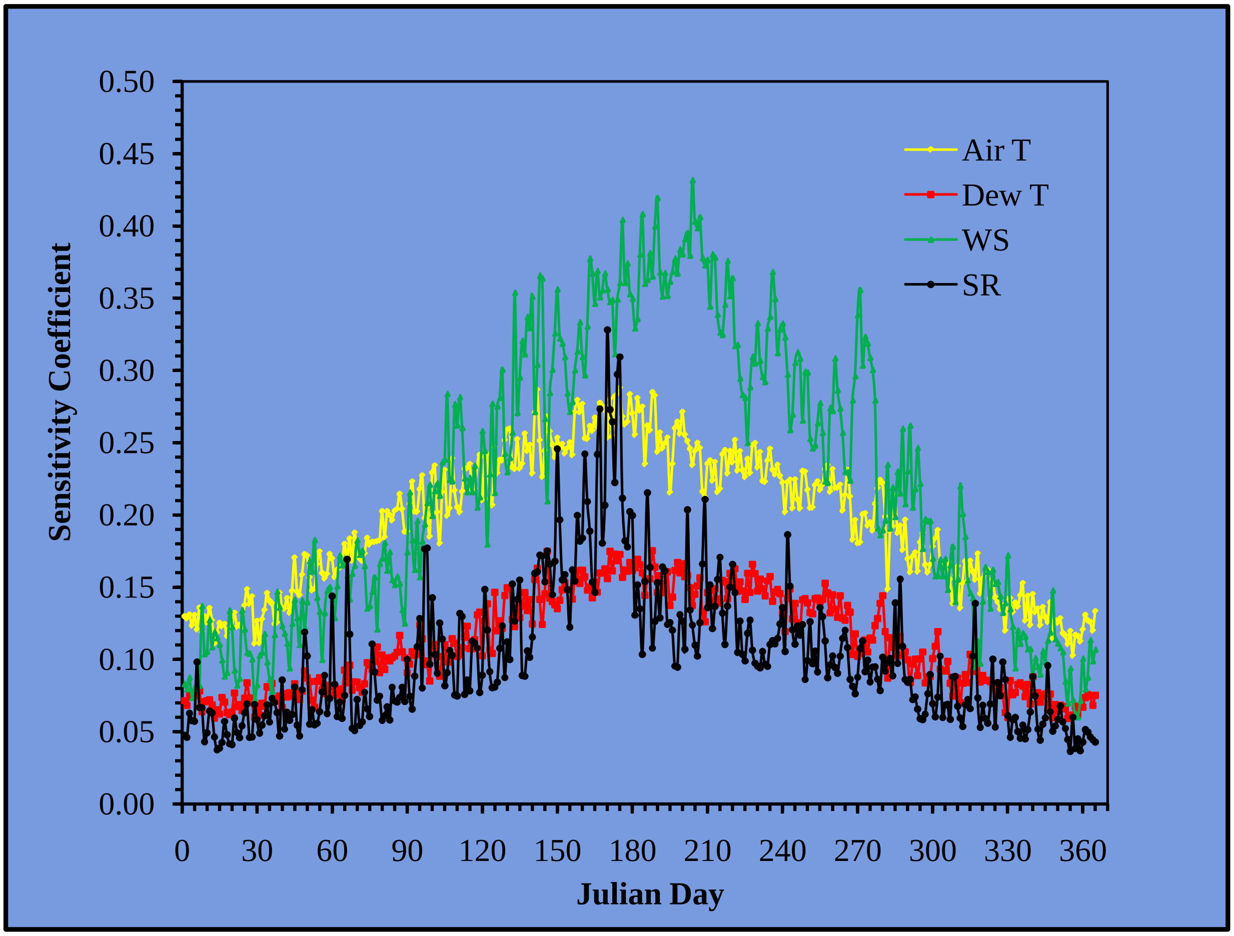


Figure 38. Daily average ETrs sensitivity coefficients for air temperature, dew point temperature, wind speed and solar radiation.

practical significance becomes very clear. In task 6, the implications of these deviations were to be evaluated by deviating the actual reference ET and crop ET inputs of a large, accurate and representative regional irrigation water estimation (planning) model used in northern Texas. These deviations will then result in actual and representative (i.e. actual value) increases or decreases of irrigation water demand on a regional scale which illustrate the full impacts of the sensitivity and need of accurate measurement of weather parameters.

Task 4

<u>Weather Sensor Degradation Analysis</u>

Methodology

The data used for this task of the project was obtained from a commercial recalibration source database. To allow usage of the data for this project, anonymity of the specific manufacturer and sensor models was agreed to with the provider. Thus, the models were coded with the nomenclature of SRSM which depicts solar radiation sensor model.

Recalibration data were available for five models of solar radiation sensors and designated as SRSM1, SRSM2, SRSM3, SRSM4 and SRSM5. The difference between the SRSM1/SRSM2 models and SRSM3/SRSM4/SRSM5 models is that the SRSM1/SRSM2 models are quantum sensors that measure photosynthetic photon flux density. The SRSM3/SRSM4/SRSM5 models are pyranometers that measure incoming solar radiation with a silicon photovoltaic detector. The SRMS2 and SRMS4 models do not have a connector at the end of the sensor cable, but rather terminate with two bare wires for manual connection to a junction block or datalogger. The difference in the SRSM3 and the SRSM5 is that the SRSM3 has a 100 ohm shunt resistor built into the wiring cable.

The commercial sensor database provided included sensor location, model number, serial number, original calibration date, original calibration value, calibration value as received, date of recalibration, new calibration value, ratio of calibration as received and original calibration, calibration drift and number of months between calibrations. Generally, it was assumed that recalibrations were done (i.e. returned to the supplier for corrective repairs) for either known error output or for routine scheduling purposes. Thus, the percent drift between calibrations was plotted against the number of months (time) since the previous calibration or repair to detect if a visual trend relationship of time versus drift or degradation was discernable. If so, a follow-up statistical relationship was to be investigated. The absolute value of percent drift was used to determine an average drift value and thus the value was not skewed, negated or altered by the negative deviations.

There were a total of 2,396 sensors for which data were available. The sensor data were separated by model number and then categorized into six geographic regions within the United States. Sensor data from locations outside the United States were classified by geographic region and climate type (i.e. humid, coastal, semi-arid, etc.). These regions were selected with an assumption of categorization that either high versus low relative humidity, salt air or air temperature may have had an effect on the relationship per respective region. The six geographic regions were designated as follows. The Northeast region included the states of Maine, New Hampshire, Massachusetts, Vermont, Rhode Island, Connecticut, New York, Pennsylvania, New Jersey, Delaware, Maryland, Virginia and West Virginia. The Southeast region included the states of Tennessee, North Carolina, South Carolina, Georgia, Florida, Hawaii, Alabama and Mississippi. The Upper Midwest region included the states of Ohio, Kentucky, Indiana, Michigan, Illinois, Missouri, Iowa, Wisconsin, Nebraska, South Dakota, North Dakota and Minnesota. The Lower Midwest region included the states of Kansas, Oklahoma, Texas, Arkansas and Louisiana. The Northwest region included the states of Washington, Oregon, Idaho, Montana, Alaska, Colorado and Wyoming. The Southwest region included the states of California, Nevada, Utah, Arizona and New Mexico. Sensor data were also analyzed solely within Texas.

Results

Graphical results are presented for the overall sensors and for the SRSM5 model since it is the most widely used in agricultural field stations. Additional and other sensor model plots, time periods and visual trends, or lack thereof, can be found in appendix C.

A plot of all the sensor models data is presented in figure 39 and contains 2,396 points.

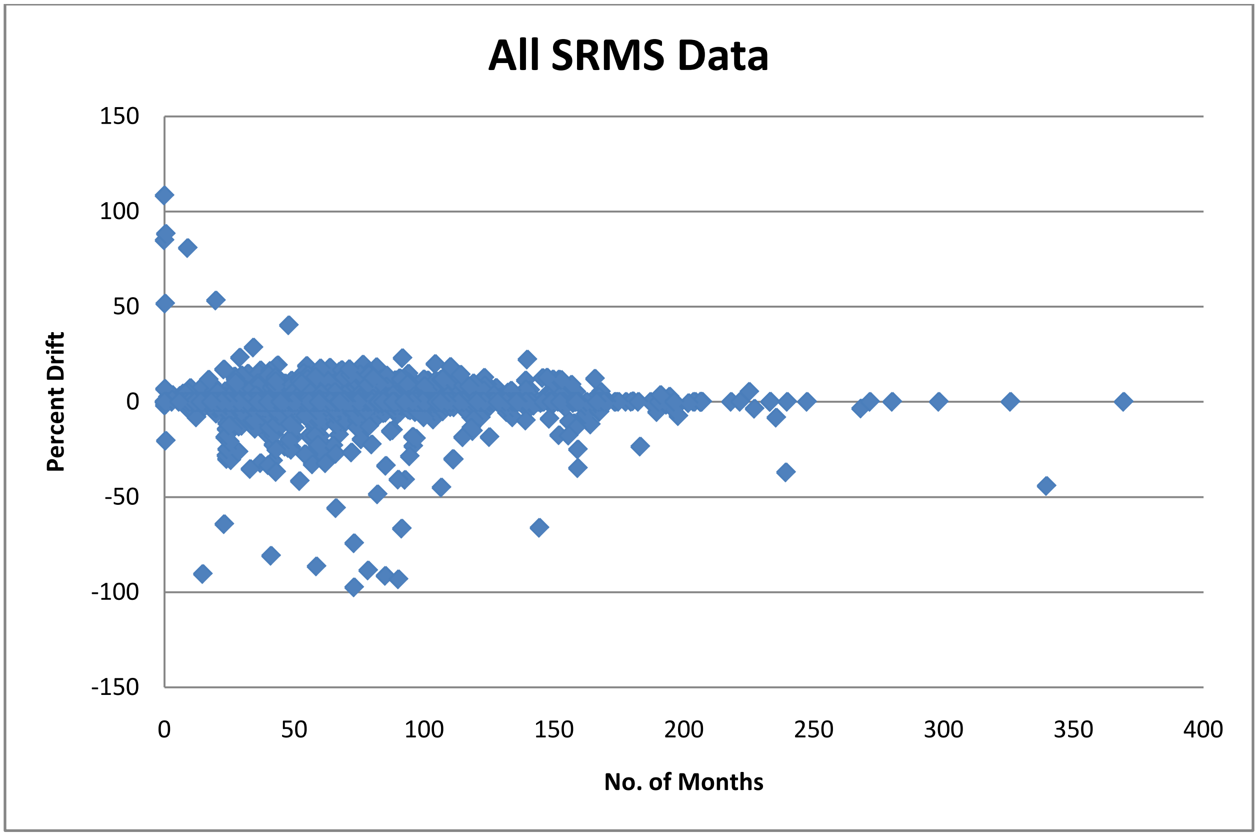


Figure 39. All solar radiation sensor data.

While the majority of values are generally within plus or minus 25% of the correct values, it should be noted that several sensors exhibited the majority of plus or minus deviations within a period between 24 to 120 months (2 to 10 years). Only rarely did any model drift exceed ±100%. Several appeared to exhibit high errors as received or installed at time zero which could either reflect a manufacturing QA/QC concern or an incorrect installation or wiring process that damaged the sensor. Given the general knowledge of the manufacturer's instrumentation calibration process, the later event is more likely. Note that the 25% deviation level is magnitudes more than the 25 W/m^2 sensitivity level evaluated in task 3, so the impact of this level of Rs error would be of significant and unacceptable impact on ETref computations, particularly during the summer period.

The data with major outliers excluded is presented in figure 40 where only sensor deviations of 30% or less were reported. The majority of deviations generally occur within a period of 120 months (10 years) and is centered around a plus or minus 10% error.

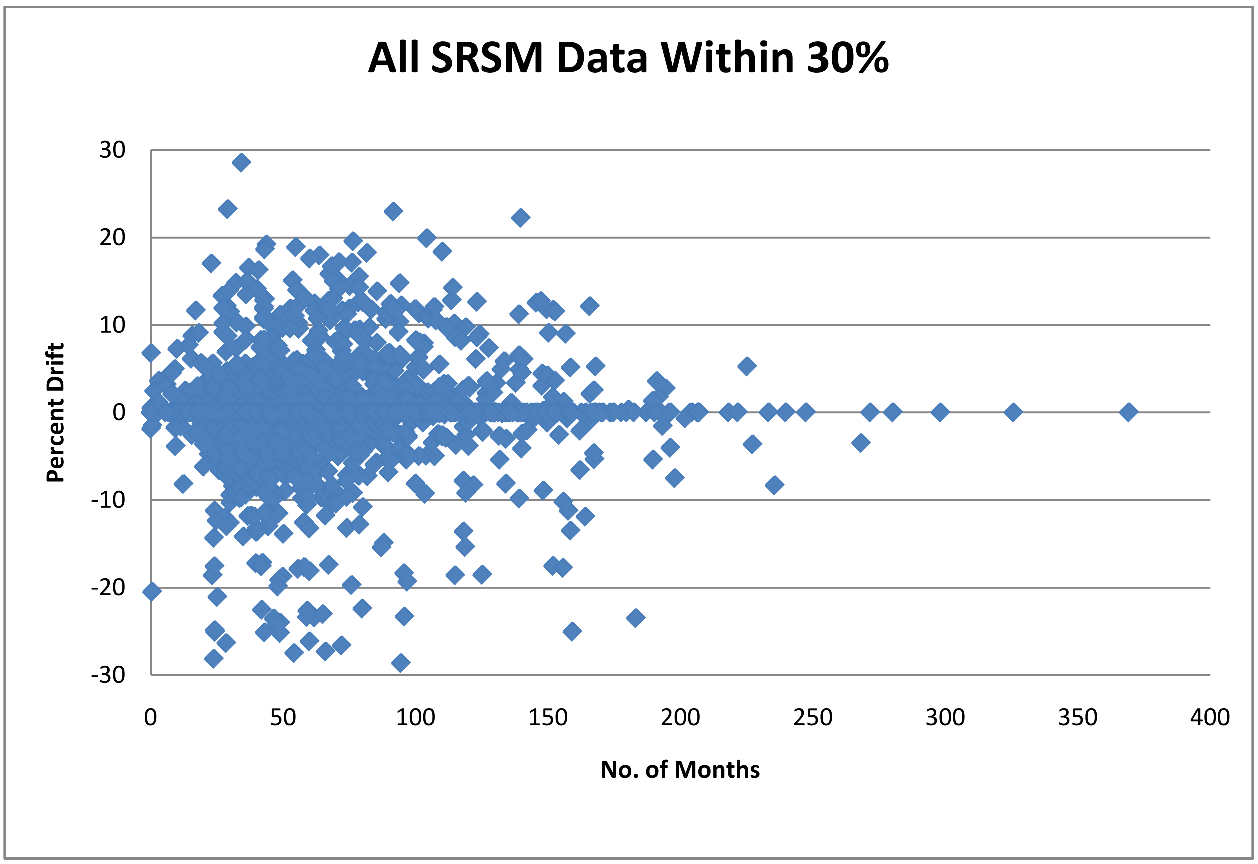


Figure 40. All SRSM data within 30 percent drift of all data.

Surprisingly, a large number of the sensors still retain a zero drift value throughout the 180 month period. The overall average absolute value of drift for all sensor models was 3.58 percent. The average period between calibrations for all sensor models was 64 months (5.3 years).

The SRSM5 sensor data for all time periods is presented in figure 41. The drift of this sensor appears much less than others in the overall plot. With the exception of the only a couple of outlier values, the deviations are limited to plus or minus approximately 10%. It is also clear that this is a "robust" sensor in multiple environments where zero or near zero drift is exhibited even after long time periods, indicating excellent sensor stability.

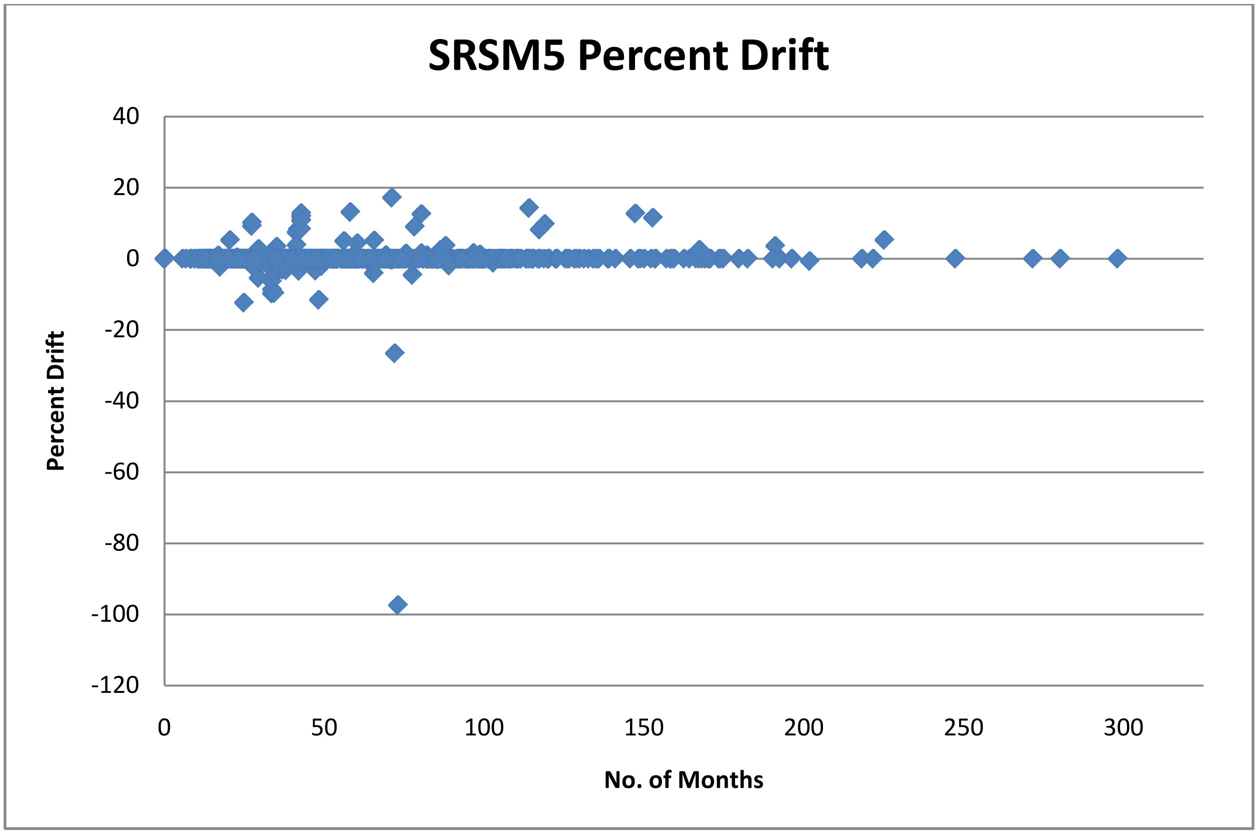


Figure 41. Model SRSM5 pyranometer percent output value drift versus time between recalibrations.

The SRSM5 model data base included 917 sensors (see figure 41). The average absolute value of percent drift for these sensors was 0.57 percent. The average overall period between calibrations was 59.2 months (~5 years). This sensor model only had 89 sensors (or < 1%) that drifted between calibrations. Separating these data by climate, we found that the SRSM5 sensors in the Northeast region had an average percent drift of 0.36 with a maximum of 9.78 and a minimum near zero. The average period between calibrations was 56 months with a maximum of 113.4 months and a minimum of 12.2 months. There were 95 model SRSM5 sensors in the Northeast region with 87 having zero drift. In the Southeast region, the SRSM5 had an average percent drift of 0.76 with a maximum of 97.45 and a minimum near zero. The average period between calibrations was 46.5 months with a maximum of 167.3 months and a minimum of 0.3 months. There were 206 SRSM5 sensors in the Southeast region, and of those, 190 had zero drift. In the Upper Midwest region the average percent drift was 1.26 with a maximum of 12.81 and a minimum near zero. The average period between calibrations for this region was 50.7 months with a maximum of 196.2 months and a minimum period of 10.6 months. There were a total of 77 model SRSM5 sensors in the Upper Midwest region, of which 64 had zero drift. In the Lower Midwest region, the average percent drift for the SRSM5 was 0.63 with a maximum of 17.16 and a minimum near zero. The average period between calibrations was 53.3 months with a maximum period of 218.2 months and a minimum of 11 months. There were 81 sensors in the Lower Midwest region with 71 having zero drift. The Northwest region had an average percent drift of 0.5 with a maximum of 26.61 and a minimum of zero. The average period between calibrations was 70 months with a maximum of 271.6 months and a minimum of 5.7 months. There were 196 SRSM5 sensors in the Northwest region, of which 175 had zero drift. In the Southwest region the average percent drift was 0.33 with a maximum of 14.24 and a minimum near zero. The average period between calibrations was 67.1 months with a maximum of 298.1 and a minimum of 6.3 months. In the Southwest region there were a total of 259 model SRSM5 sensors with 237 having zero drift.

Analysis of a subset of the SRSM5 dataset (see figure 42) for a time period of 24 months reveals the stability of this model sensor again with less than approximately 1 percent drift.

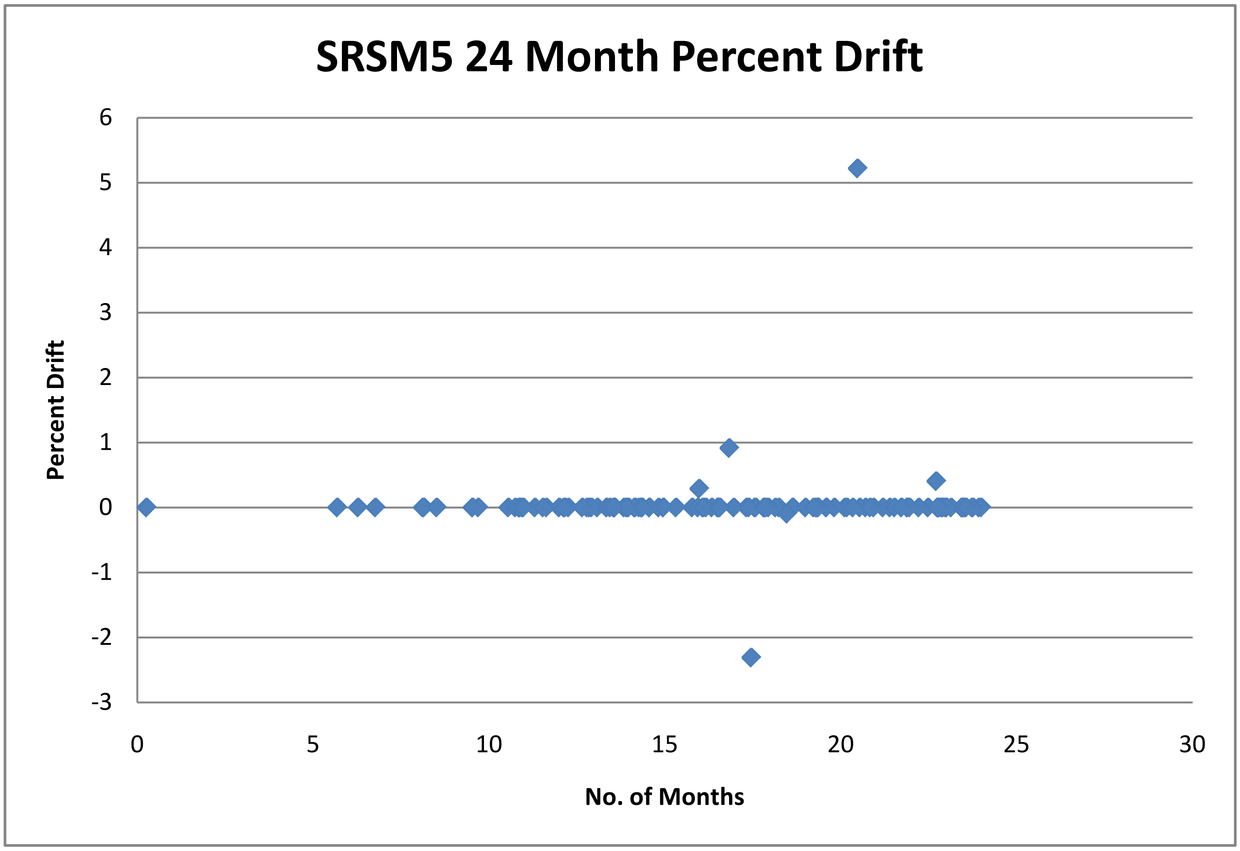


Figure 42. Model SRSM5 pyranometer percent output value drift versus time between recalibrations within 24 months.

Implementation of routine QA/QC procedures should address the minor number of deviations that occur with this sensor as compared to the clear sky radiation potential. Given the small number of drift deviations, no degradation relationship would prove useful as the linear relationship's slope, intercept and coefficient of determination all approach zero.

Solar radiation sensor data for Texas were separated to analyze for possible trends within the state. Within Texas, there were data for 2 SRSM1 sensors, no SRSM2 sensors, 48 SRSM3 sensors, 15 SRSM4 sensors and 32 SRSM5 sensors. The SRSM3 was the most common sensor in Texas; however, the SRSM5 sensor was the most common in the dataset. For this reason, and due to the limited number of other model sensors, the SRSM3 and SRSM5 sensors are included in this portion of the analysis.

The SRSM3 sensor had an average absolute value percent drift of 6.7 percent, with a maximum drift of 108.4 percent and a minimum of zero. The average length of time between calibrations was 59.2 months (~5 years) with a maximum recalibration period of 168 months (12 years) and a minimum of zero months. Of the 48 sensors for which there were data, only 13 (27%) had zero drift (see figure 43). No apparent relationship exists between time of service and drift for the sensors located in Texas. One sensor that was recalibrated, as received, had 108 percent drift while another sensor, having been used for 168 months between recalibrations, had a drift or calibration difference of 5.2 percent.

The SRSM5 had only 1 of the 32 sensors (3%) exhibiting drift located in Texas (see figure 44) and this sensor only drifted 1.1 percent. The period between calibrations ranged from 14 months to 171 months and had an average period of 58 months. The sensor that drifted had a recalibration period of 64.5 months.

Due to the limited number of sensors for which data were available within Texas, an analysis of shorter time intervals could not be adequately conducted. Using all the solar radiation sensors located in Texas, no correlation between time and drift could be established, as were with the sensor data for all models in all geographic regions. The SRSM3 model was the most used sensor in Texas, however, the SRSM5 appears to be the most reliable.

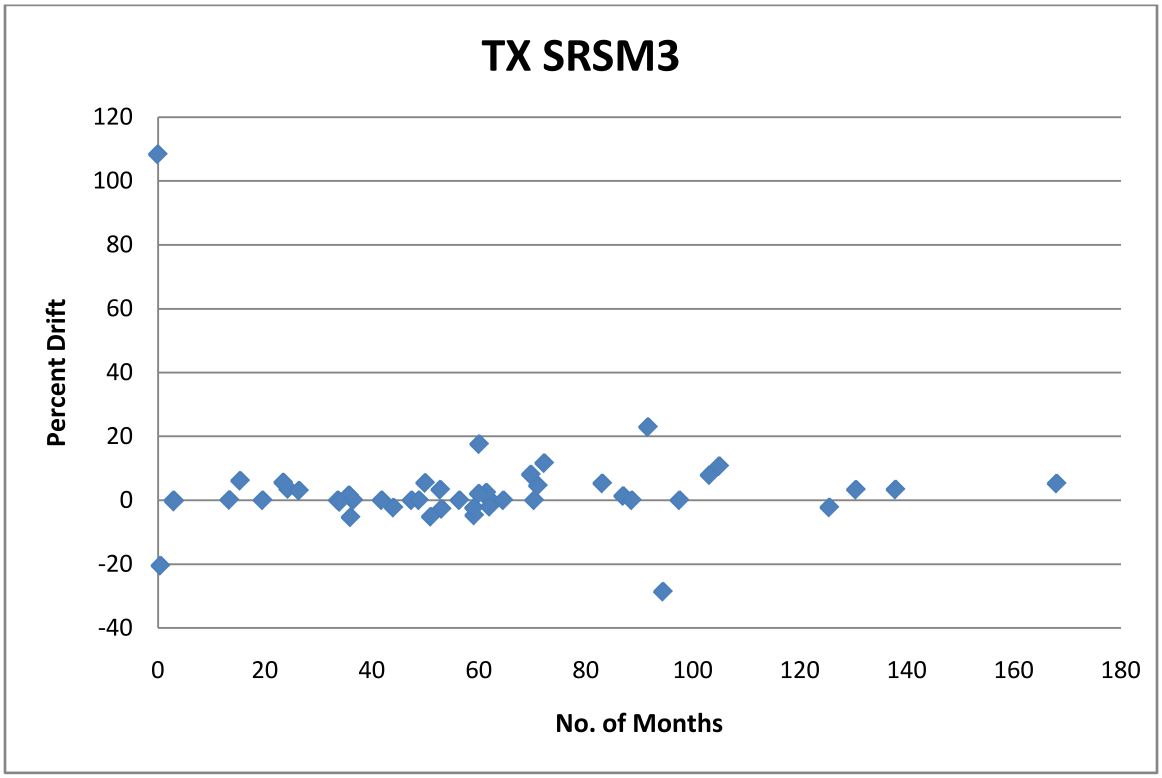


Figure 43. Model SRSM3 pyranometer percent output value drift versus time between recalibrations within Texas.

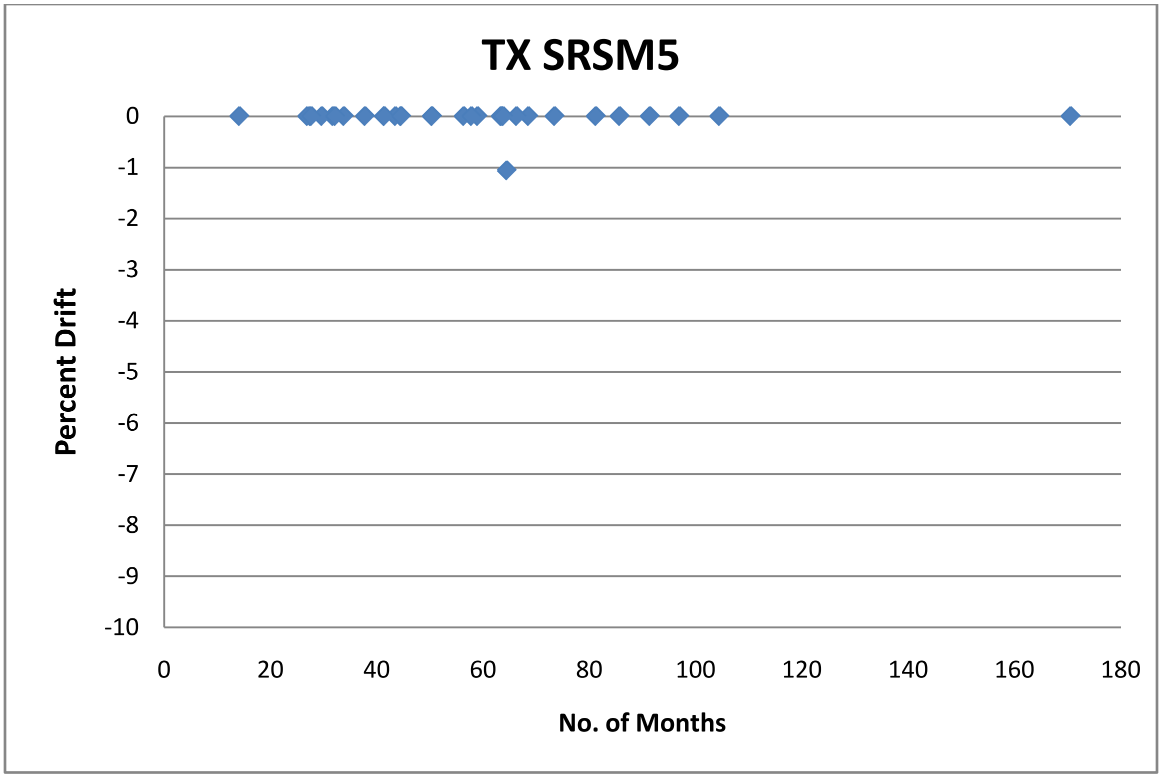


Figure 44. Model SRSM5 pyranometer percent output value drift versus time between recalibrations within Texas.

Task 5

Compilation and Comparison of Parameter Data.

Methodology

The analysis methodology used for this task of compilation and comparison of parameter data included navigating the network websites to collect available data sets, finding available paired data from two networks with meteorological stations in the same vicinity, viewing the data side by side and comparing each data point. Data sets were gathered to view the available parameters and different outputs. Agricultural networks were compared with non-agricultural networks to evaluate and demonstrate the differences caused by factors such as site selection. When datasets were obtained from different networks with stations in the same location, the data were put into a spreadsheet with measurements compared side by side. The absolute values of the differences in measurements were taken to show the relative difference between the two networks. Negative differences result in cases where one network will have a higher value than the other network at one measurement interval. Once the differences were calculated, the percentage difference was calculated using the agricultural network data as the base (control) to show the difference reflected from the site for comparative ET purposes. It was assumed that the agricultural network had the more representative data for ET purposes. At the end of each comparison, the maximum and minimum differences were calculated along with the average percentage difference. The average percentage difference was primarily calculated to assess the relative scale of the differences. Some parameters have small absolute difference values that actually equate to a large relative percentage difference.

One potential cause of additional error in this process is the measurement itself or parameter units. Not all networks use the same units, resulting in conversion round-off errors. This is particularly true as most network sites do not disseminate the full accuracy of the recorded or computed values. These errors may seem small on an hourly or daily basis, but can become significant when expanded and compiled over the entire growing season. The units used in the comparisons were degrees Fahrenheit for temperature, meters per second for wind speed and percentage for relative humidity. Measurements obtained that were not recorded in these units were accordingly converted. These units were chosen for the fact they were the most common units used by the data sources. Other parameters, such as solar radiation, were not available for all networks so no standard unit was used. Instead, the units provided were used and if conversion was necessary, the measurements were converted to the more common of the two units. Wind speed was converted to meters per second due to the fact that it is the unit of measurement used in the standardized ET equation. The ASCE wind speed height adjustment algorithm (Allen et al., 2005) below was utilized as needed in the analysis and is represented by:

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.42)} \qquad (1)$$

where

u_2 = wind speed at 2 m above ground surface (m/s),

u_z = measured wind speed at z m above ground surface (m/s),

z = height of measurement above ground surface (m).

Some comparisons were made using RAWS station data. Expectations for these comparisons were that the differences in measurements would be smaller with these stations than with other network stations. The reason for this assumption is that the RAWS stations typically undergo documented scheduled maintenance and implemented QA/QC procedures. These stations are monitored and maintained by government agencies and used in fire prediction, monitoring and research. These purposes generally imply a high standard maintenance and data accuracy. RAWS stations also have standards for site location, whereas personal weather stations generally do not. Some differences may also occur between the two sources due to site selection of agricultural sites attempting to emulate field representation locations. RAWS stations are generally located in areas not used for agriculture which can, for instance, have a greater amount of large vegetation at times that can raise the relative humidity through transpiration and also affect the "true" nominal wind speeds.

Some networks, particularly the iAIMS network (a clearinghouse type website), did not provide sufficient data parameters for some locations to allow comparison. The iAIMS network collects current and historical data from any available source. This results in the network showing stations that have not collected any new data in many (up to 80) years. In addition, many locations only provide data for the parameters of maximum and minimum air temperature and precipitation. Although these networks claim a large number of stations within the state, the number useful for computation of reference ET is significantly lower than with other sources. Comparisons were still made using these sites to show the differences between the agricultural based ET network values and for thoroughness of the project.

Precipitation is an interesting parameter in that natural and actual variations in values can be large even over relatively short distances (high spatial variability). This makes comparisons between networks for this parameter difficult to adequately perform, especially in a manner that does not imply measurement errors or differences. Due to this fact, precipitation data were excluded from the data comparisons performed in this task.

Some networks measure parameters such as maximum wind speed which are not necessary or pertinent for ET calculations for agricultural applications. These variables were, however, included in data comparisons to illustrate differences in measurements between two networks. Even though they may not be significant measurements in regards to ETref, these measurements show differences in values that may be caused by site selection, sensor error or other causes.

Solar radiation average differences can be skewed by zero values collected from nighttime hours. Two sources can have vastly differing values when only non-zero values are collected but a low average difference due to the zero values encountered at night. To offset this computational bias, zero value data points for solar radiation were excluded, allowing for determination of the difference between actual measurements during the daylight hours that affect ET.

In comparisons of hourly data, data were selected for at least a 24 hour time period to be used in the comparison. For daily data, comparisons used selected data for a one month time period, if possible. An attempt was made to compare the most frequent measurement intervals, usually hourly, since a more frequent measurement interval can be summed to provide more accurate daily values. In some cases only daily data were available. Variable selection and measurement frequency were limited to the data available from the websites.

Results

For this discussion, only select paired datasets from the different networks/sources with stations located in the same vicinity will be presented. Additional comparisons of parameter data from similar paired sites are included in appendix D.

Data from the Texas ET Network and the Desert Research Institute, which monitors the RAWS station for Huntsville, TX, provided hourly measurements for comparison for the date of June 8, 2010 for air temperature, relative humidity, solar radiation and wind speed. The RAWS stations measure wind speed at a height of 6.1 m (20 ft) and had to be adjusted to a 2 m (6.6 ft) height using equation 1. The air temperature measurements had an average difference of 0.6 ^{o}C (1 ^{o}F) with a maximum difference of 2.8 ^{o}C (5 ^{o}F) and a minimum difference of 0 ^{o}C (0 ^{o}F). The average percentage difference over the period was 1.3 percent. The relative humidity measurements had an average difference of 9.4 percent with a maximum difference of 37 percent and a minimum difference of 1 percent. The average percentage difference for relative humidity was 12.2 percent. The average difference in solar radiation was 0.09 MJ/m^2/day with a maximum difference of 0.25 MJ/m^2/day and a minimum difference of 0 MJ/m^2/day. The average percentage difference was 23.9 percent. For wind speed the average difference was 0.89 m/s (1.99 mph) with a maximum difference of 1.99 m/s (4.45 mph) and a minimum difference of 0.01 m/s (0.02 mph). The average percentage difference for wind speed was 200 percent.

Graphical comparisons of the hourly data for these two sites are presented in figure 45 through figure 48 for the parameters of maximum and minimum air temperature, relative humidity and wind speed. The comparisons yielded mixed results as some parameters are reasonably close (air temperature, relatively humidity and solar radiation) with wind speed differing considerably. Thus, reference ET computed using these data would result in significantly different ET values since the sensitivity analysis in task 3 indicated that wind speed was the most influencing factor on reference ET computations. Since specific location information typically is not included with the site data, it is not possible to determine why the wind deviation is so severely different between the sites and period of interest.

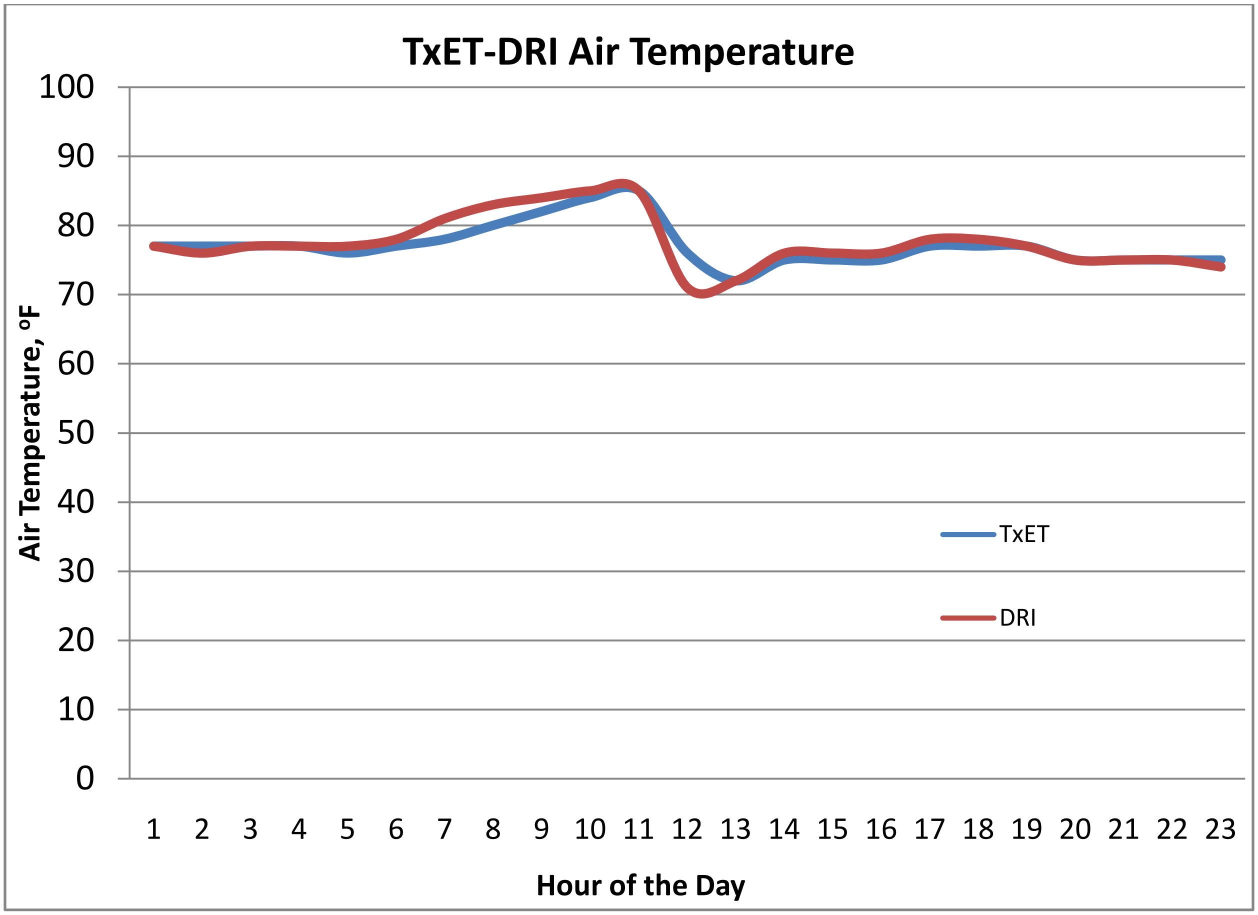


Figure 45. Comparison of hourly air temperature data for the Huntsville stations.

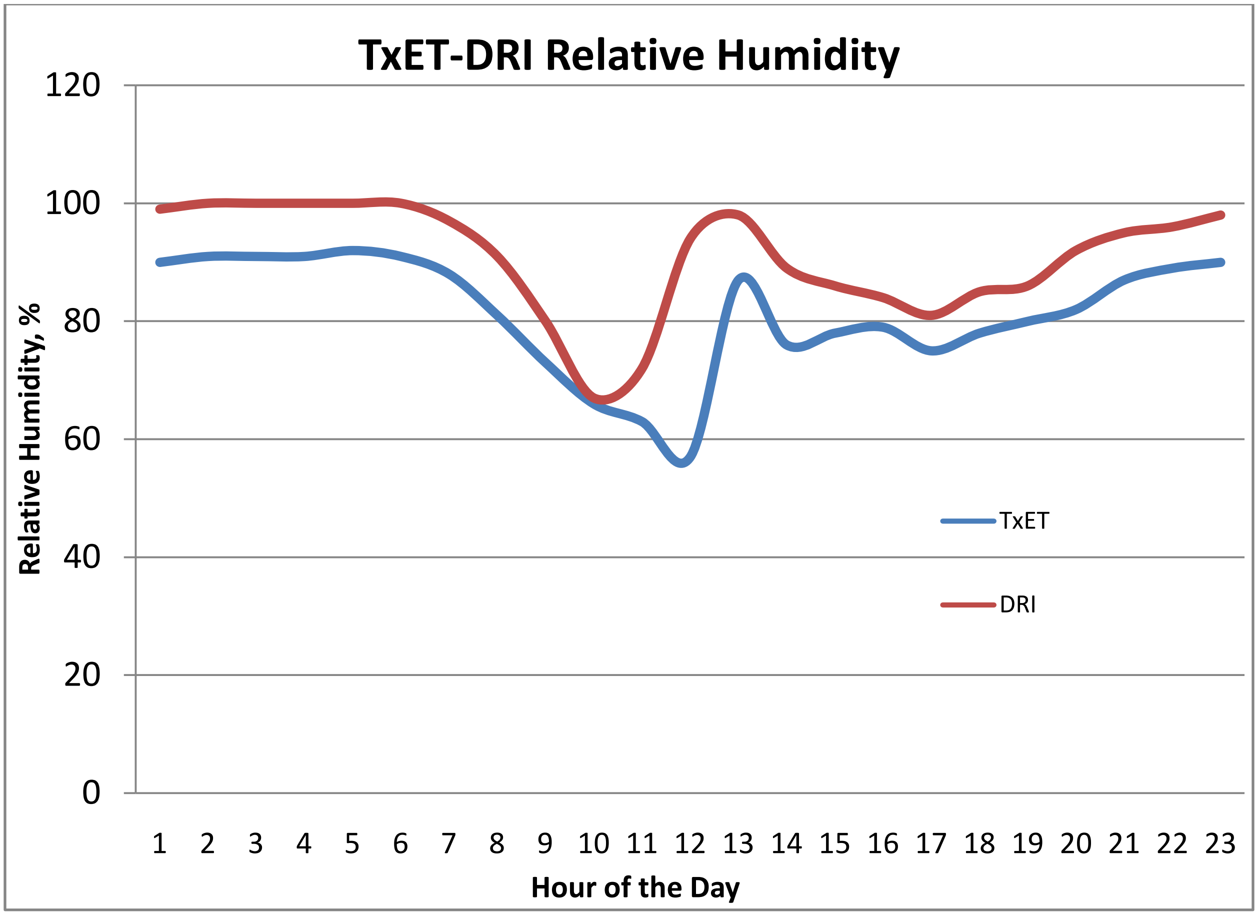


Figure 46. Comparison of hourly relative humidity data for the Huntsville stations.

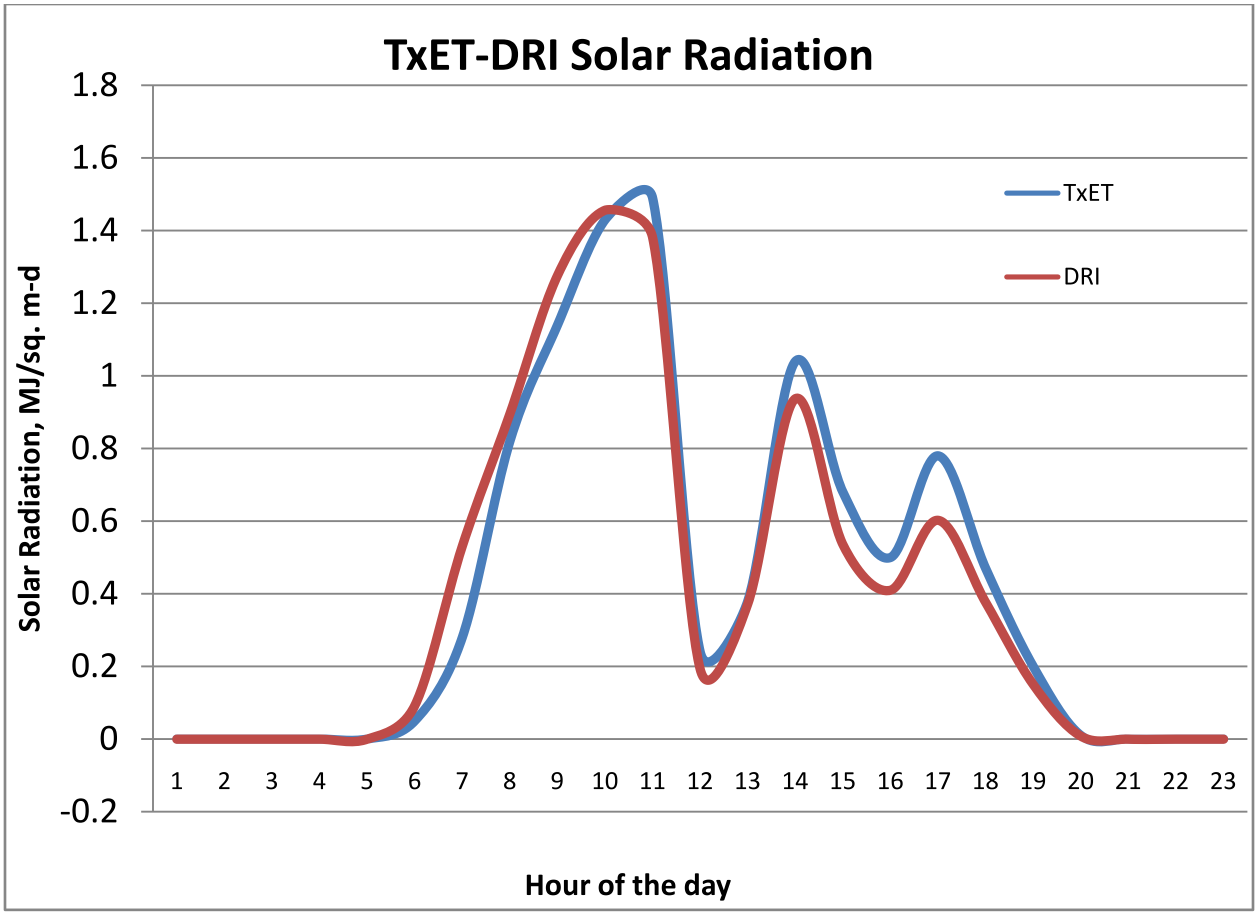


Figure 47. Comparison of hourly solar radiation data for the Huntsville stations.

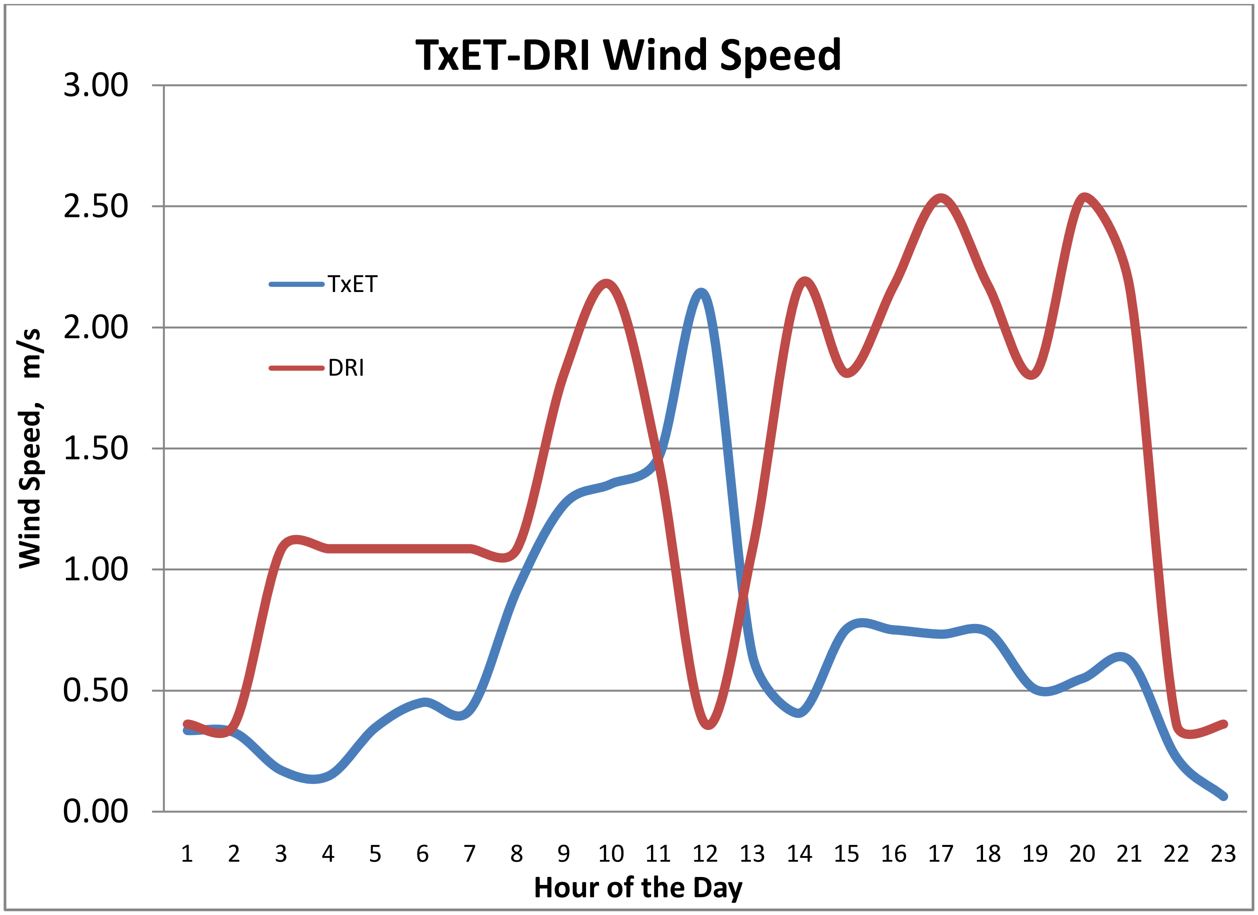


Figure 48. Comparison hourly wind speed data for the Huntsville stations.

A similar analysis using the same sites for comparison of daily values for July 2010 daily parameter values are presented in figure 49 through figure 52. Data again included maximum and minimum air temperature and relative humidity. Note that the Texas ET network only provides daily wind speed values as sampled at 4am and 4pm and thus a wind speed comparison is not included. This comparison also includes reference ET (PET from the TxET and Penman-Monteith ET from the DRI). The average daily difference in PET was 1.02 mm (0.04 in.), with a maximum difference of 2.03 mm (0.08 in.) and a minimum difference of 0 mm (0 in.). The average daily percentage error was 21.04 percent. The maximum air temperature had an average difference of 0.6 ^{o}C (1 ^{o}F) with a maximum difference of 1.7 ^{o}C (3 ^{o}F) and a minimum difference of 0 ^{o}C (0 ^{o}F). The average percentage difference for maximum temperature was 1.1 percent. The minimum air temperature had an average difference of 0.4 ^{o}C (0.65 ^{o}F) with a maximum difference of 1.1 ^{o}C (2 ^{o}F) and a minimum difference of 0 ^{o}C (0 ^{o}F). The average percentage difference for minimum air temperature was 0.86 percent, which is excellent. For relative humidity, the average difference was 34 percent with a maximum difference of 44 percent and a minimum of 27 percent. The average percentage difference for relative humidity was 79 percent, which appears unacceptable.

It should be noted that values from data sites are often missing as illustrated regarding PET from the DRI in figure 49. For this particular DRI dataset, solar radiation data was missing for several days which did not allow for the calculation of PET. It is left up to the user to determine as to how to deal with missing data, which can be particularly common among miner sites. (It should be mentioned that some of the larger ET networks in the western U.S. offer statistically interpolated set of values for missing periods because many models and applications require a continuous data stream.) For the relative humidity difference, it appears that a siting problem is the issue since the trends of both stations are similar throughout the time period and the difference is consistent. The problem though is that the user does not know which site provides the more representative data set for agricultural purposes as there is no metadata type available for the sites. Nonetheless, the impact of the deviation on ET computation is less than it would be for the other parameters as RH affects DewT, which was the least sensitive of the parameters influencing ET computation. It is up to the user to determine if the data and associated errors are acceptable for their ET application(s). If the application has small consequences, it may be acceptable, but if widespread interferences are evident, this level of accuracy may not be suitable. (This will be illustrated with a regional inference example in Task 6.)

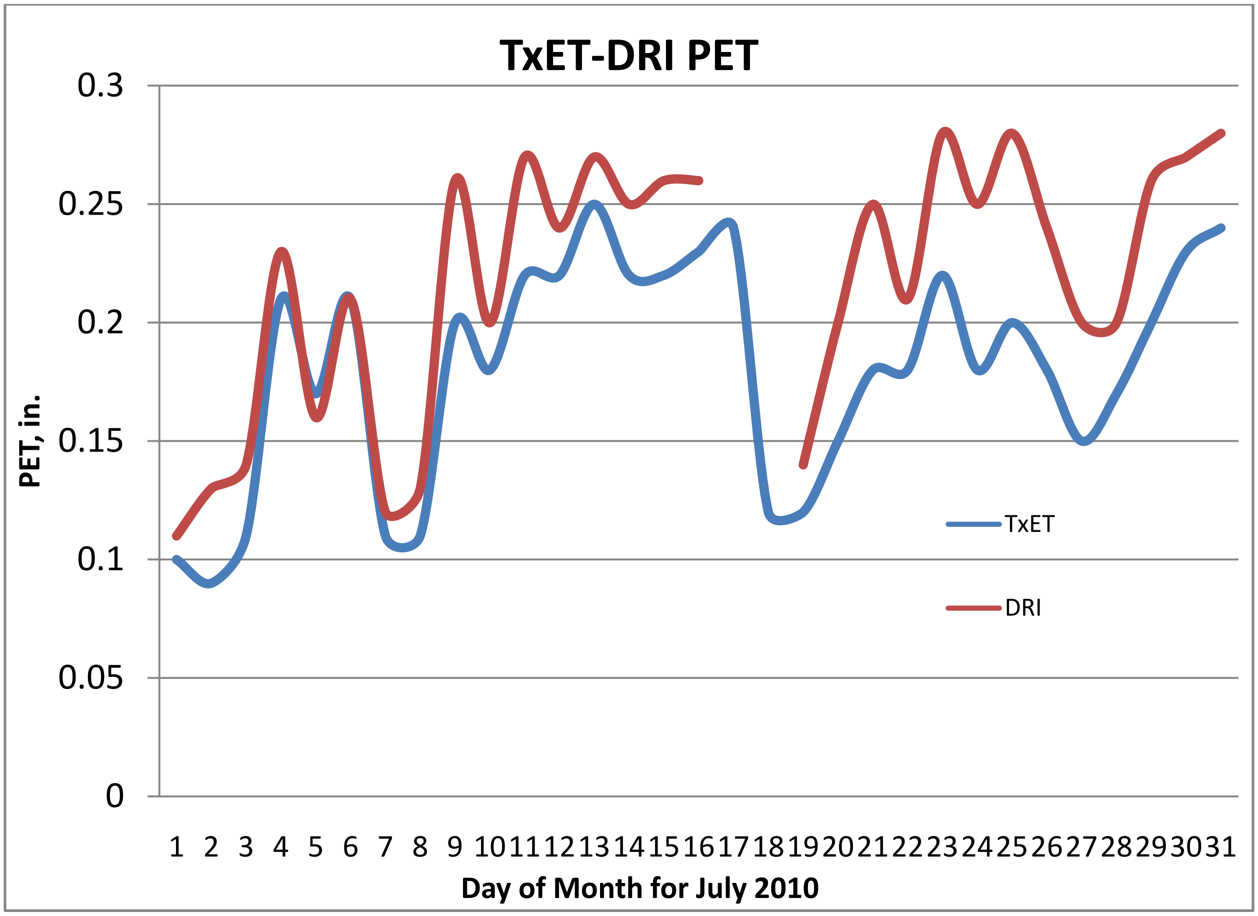


Figure 49. Comparison calculated from daily data from the Huntsville stations.

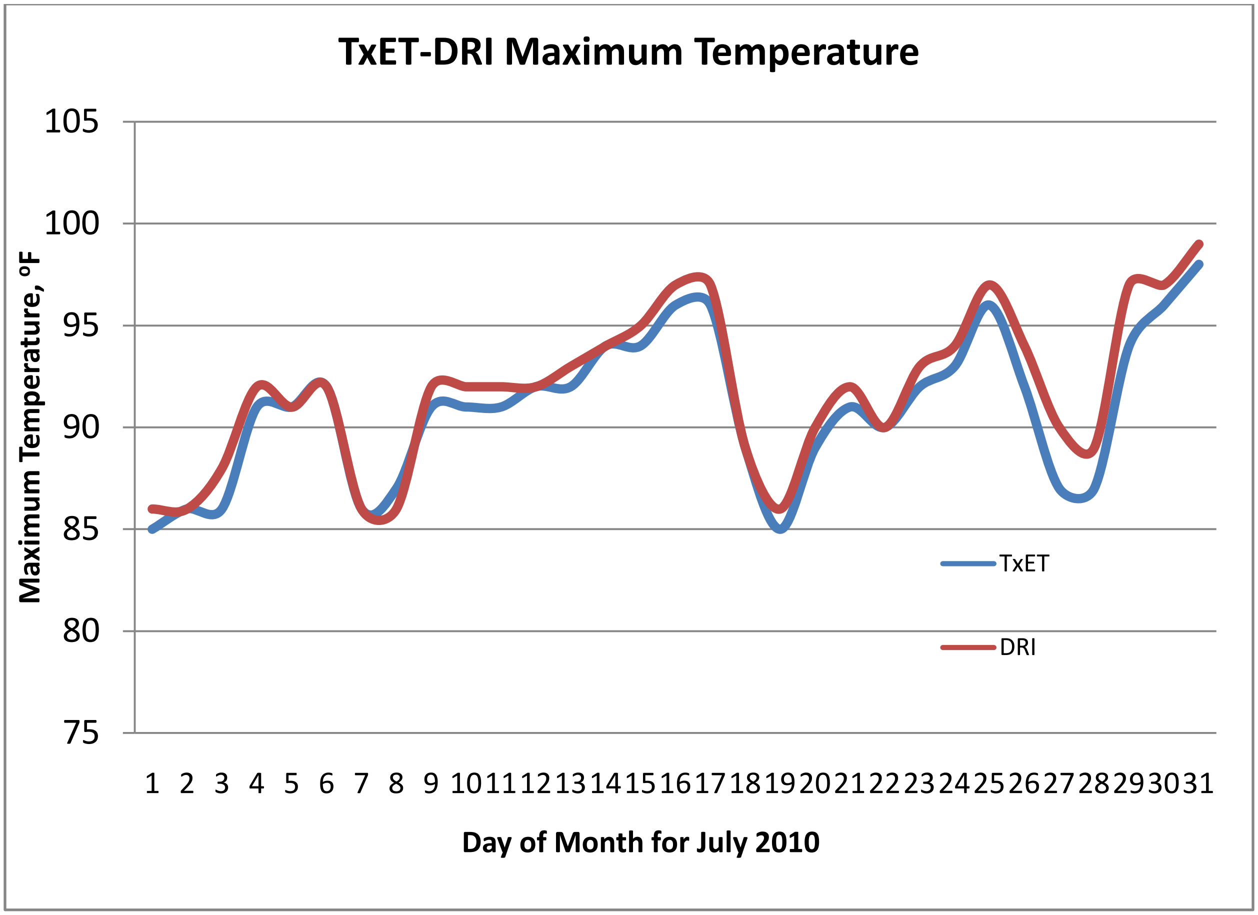


Figure 50. Comparison daily maximum temperature data from the Huntsville stations.

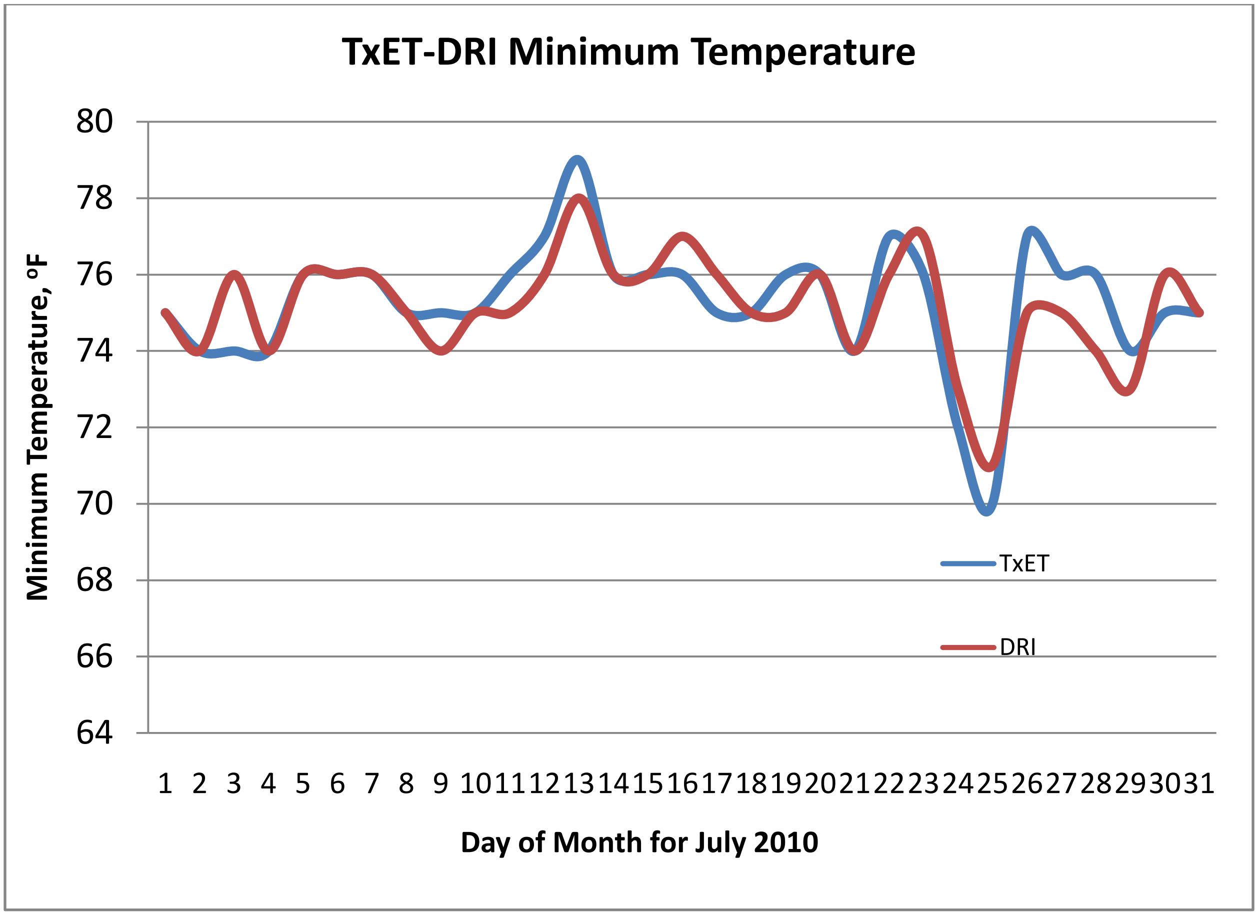


Figure 51. Comparison of daily minimum temperatures from the Huntsville stations.

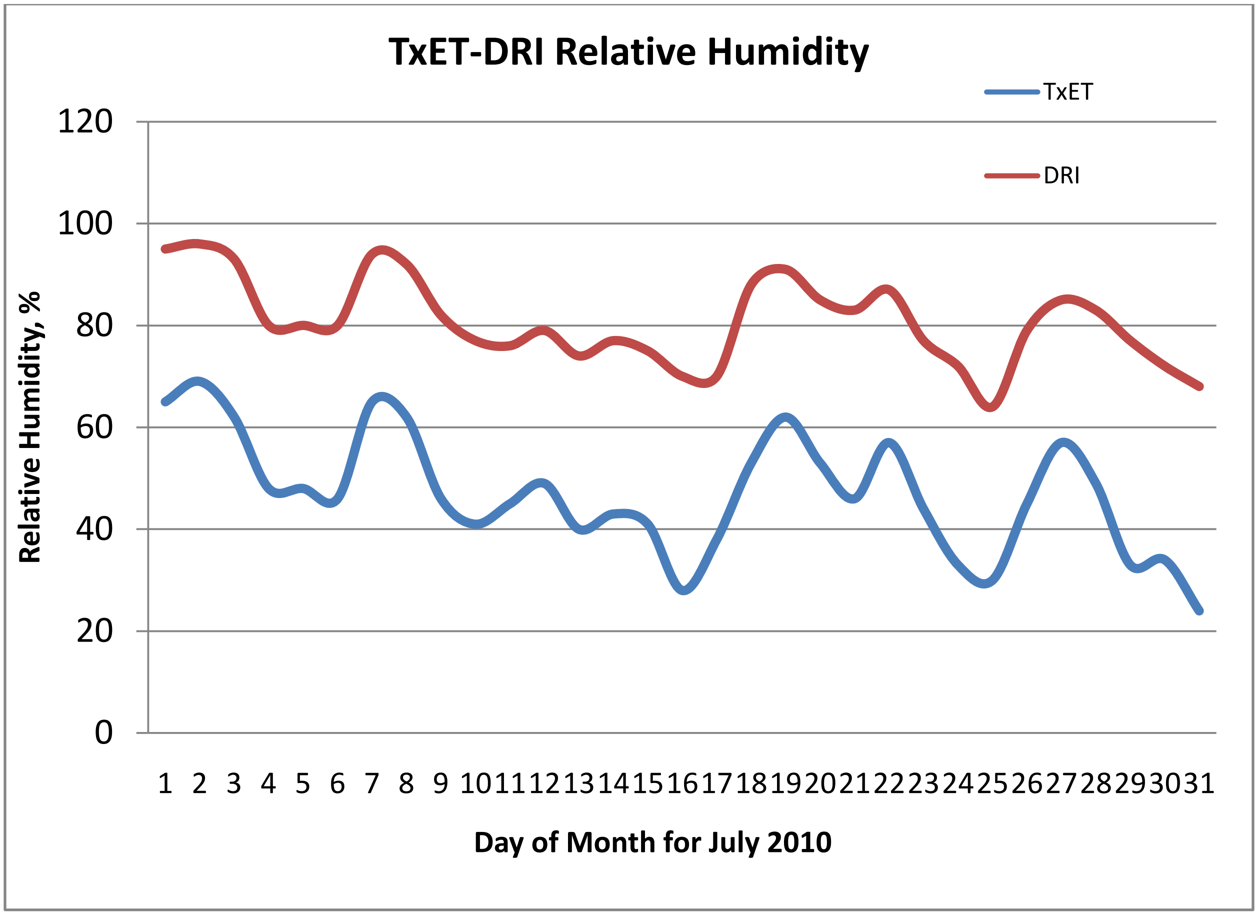


Figure 52. Comparison of daily relative humidity data from the Huntsville stations.

A similar station data comparison in an irrigated region was conducted for a location in the Texas High Plains region. Hourly data from 26 July, 2006 compared from the TXHPET network and the West Texas Mesonet stations at Lamesa included relative humidity, air temperature, wind speed and solar radiation (see figure 53 through figure 56). The wind speed values from the WTM were recorded at 10 m (33 ft) and had to be adjusted to 2 m (6.6 ft) using equation 1. The average difference in relative humidity was 6.6 percent with a maximum difference of 21 percent and a minimum difference of zero. The average percentage difference for relative humidity was 17 percent. The average difference in air temperature was 1.99 ^{o}C (3.59 ^{o}F) with a maximum difference of 3.89 ^{o}C (7 ^{o}F) and a minimum difference of 0 ^{o}C (0 ^{o}F). The average percentage difference was 4.4 percent. For wind speed, the average difference was 1 m/s (2.24 mph) with a maximum difference of 1.9 m/s (4.25 mph) and a minimum difference of 0.11 m/s (0.25 mph). The average percentage difference for wind speed was 43.1 percent. For solar radiation, the average difference was 191 W/m^2 with a maximum difference of 307 W/m^2 and a minimum difference of 5 W/m^2. The average percentage difference was 71 percent.

Comparisons of these data appear to be fairly good except for the higher RH values and lower wind speeds in the morning hours of the WTM site which could indicate that either higher forage conditions or more wind retardation factors are present at the WTM site as compared to the TXHPET site. The anomaly of the dip in the WTM site Rs values indicate that some sort of shading occurred for a few hours, possibly from a bird shadow or obstacle shading. This Rs dip would impact total ET for the day and reflects the need of QA/QC and adjustment techniques discussed in Task 2. This WTM data should not be used with large scale inference applications without correction.

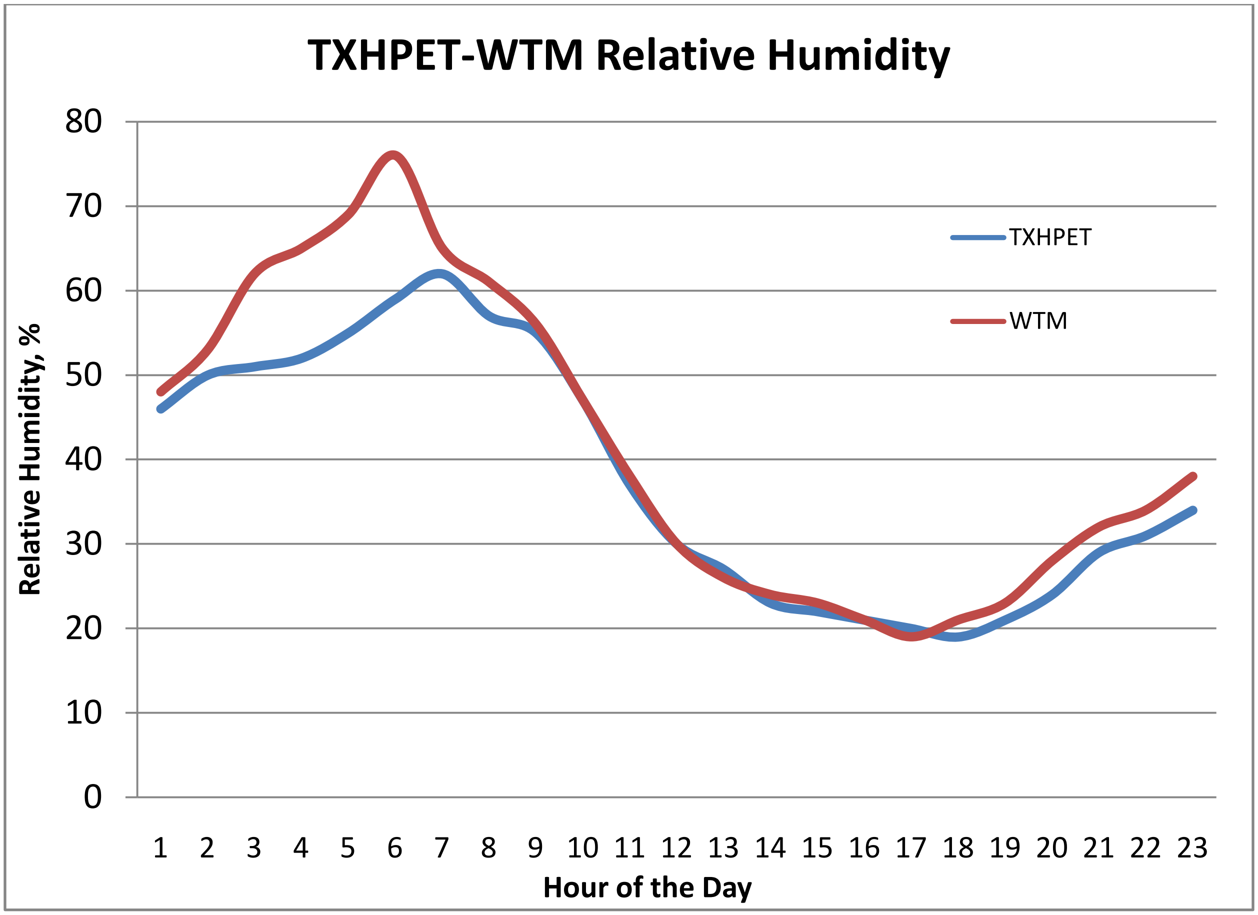


Figure 53. Comparison of hourly relative humidity data from the Lamesa stations.

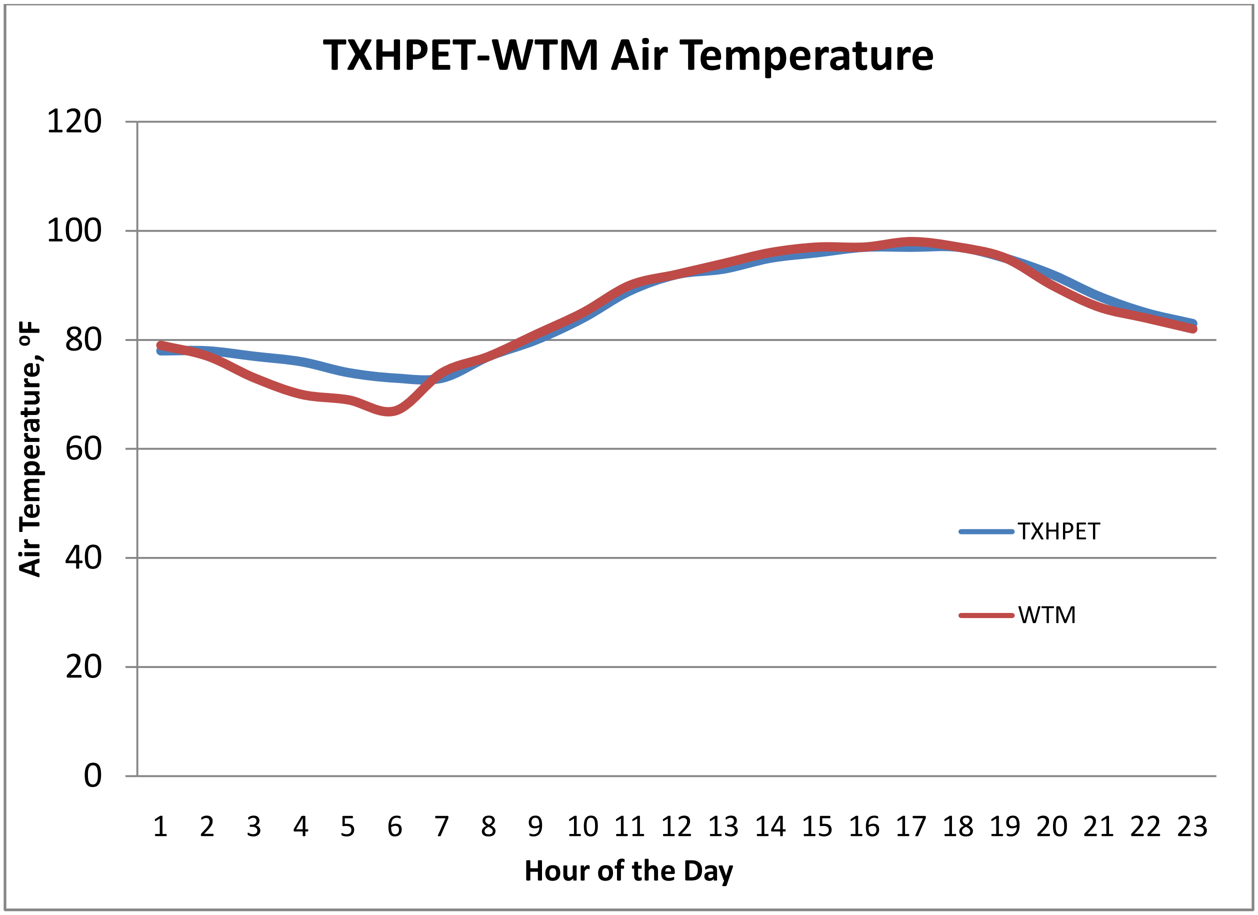


Figure 54. Comparison of hourly air temperature data from the Lamesa stations.

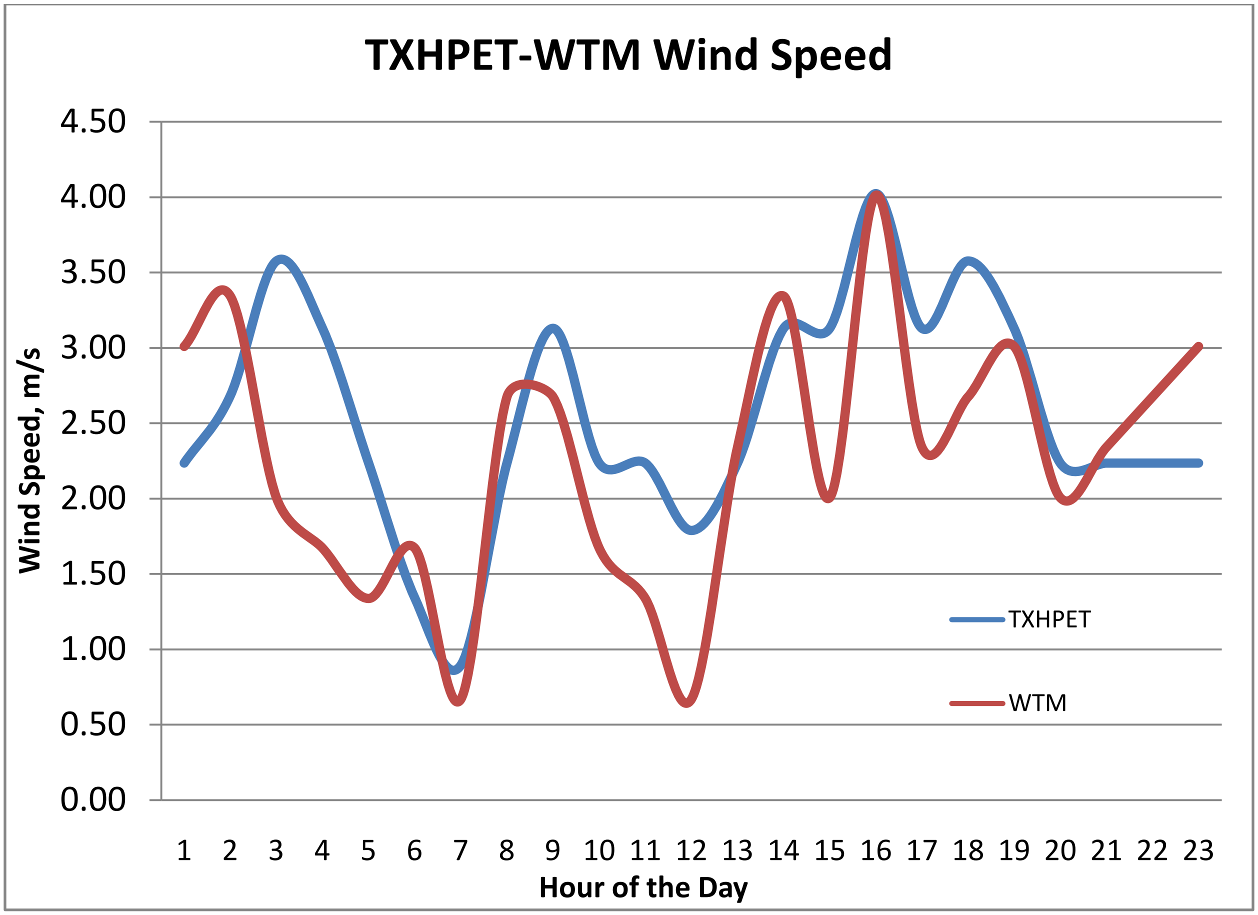


Figure 55. Comparison of hourly wind speed data from the Lamesa stations.

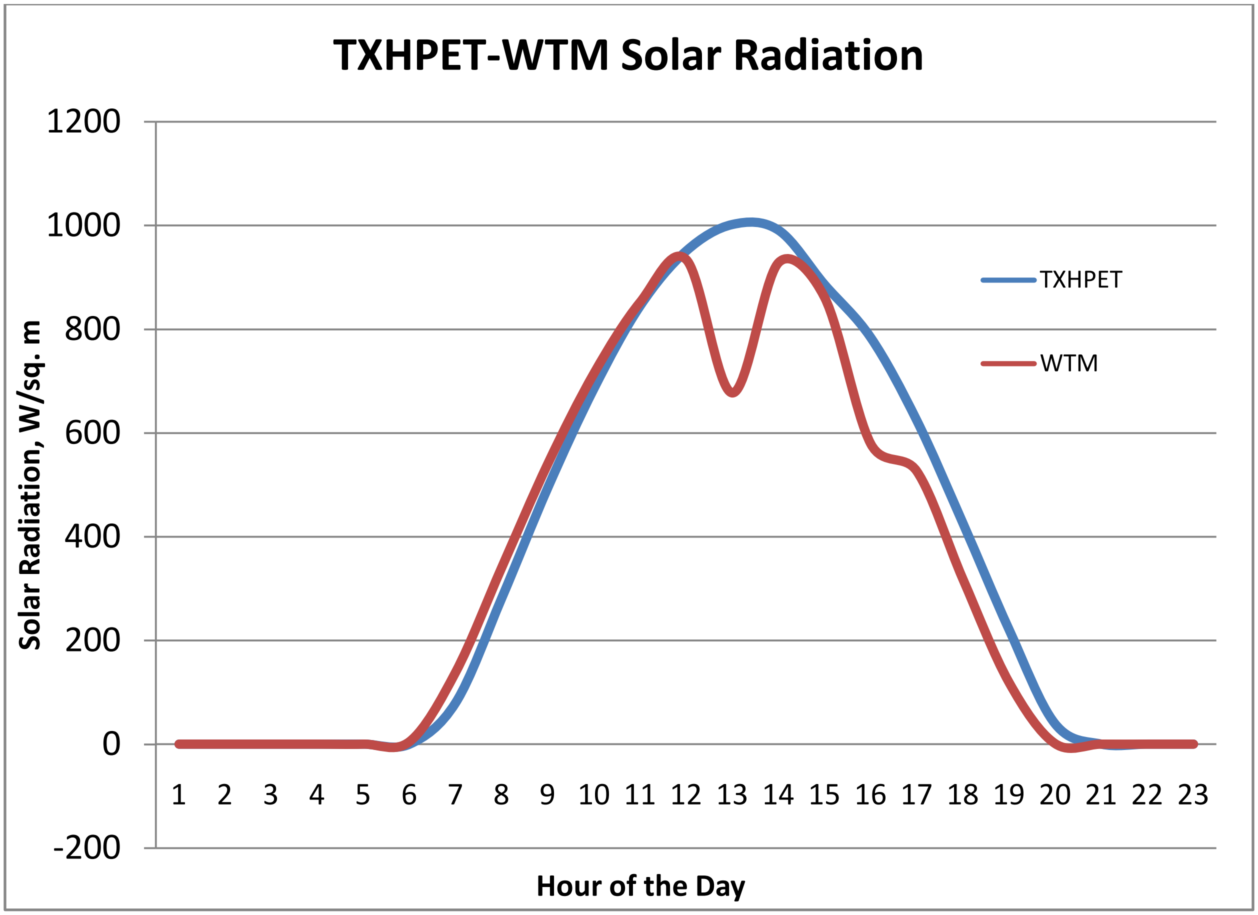


Figure 56. Comparison of hourly solar radiation data from the Lamesa stations.

Average differences for each parameter for all selected networks were summarized separately for hourly and daily measurements (see table 4 and table 5). The average difference between two respective networks for each parameter was tabulated and an average was taken for those parameter values. These averages give an indication as to the error that can be expected when using data from a network that was not designed for agricultural use. For daily measurements, the average difference between all networks for maximum air temperature was 1.69 ^{o}C (3.04 ^{o}F). The average difference for minimum air temperature was 0.74 ^{o}C (1.34 ^{o}F). The average difference for average air temperature was 0.9 ^{o}C (1.63 ^{o}F). The average difference for wind speed was 1.32 m/s (2.95 mph). The average difference for relative humidity was 17.7 percent. For the hourly data, the average differences were 1.23 ^oC (2.23 ^oF) for air temperature, 6.4 percent for humidity, 1.04 m/s (2.32 mph) for wind speed, 1.08 ^oC (1.96 ^oF) for dew point temperature and 106 watts per square meter for solar radiation.

Table 4. Average differences in hourly data for the paired data source comparisons.

Average Differences for Hourly Values					
Paired Networks or Data Sources	**Temp (^{o}F)**	**RH (%)**	**Rs (W/m^2)**	**WS (m/s)**	**Dew T (^{o}F)**
TxET-DRI	1	9.35	25	0.89	
TxET-MW	1.91	4.71		0.33	
TXHPET-WTM	3.59	6.59	191	0.99	
TXHPET-WTM2	2	4.54	101	0.79	
TXHPET-WU	1.49	5.29		1.4	2.43
WTM-WU	3.39	8.14		1.85	1.48
Averages	**2.23**	**6.44**	**106**	**1.04**	**1.96**

Table 5. Average differences in daily data for the paired data source comparisons.

Average Differences for Daily Values					
Paired Networks or Data Sources	**Tmax (^{o}F)**	**Tmin (^{o}F)**	**Tavg (^{o}F)**	**WS (m/s)**	**RH (%)**
CWP-iAIMS	4.7	1.73	2.16	0.27	
CWP-WU	2.67	1.08	1.63	3.4	14.02
TxET-DRI	0.97	0.65			33.71
TxET-NCDC	2.93	1.65			5.15
TXHPET-iAIMS	4.86	1.45			
TXHPET-NCDC	2.11	1.49	1.09	0.3	
Averages	**3.04**	**1.34**	**1.63**	**1.32**	**17.63**

Summary

Comparison of data parameters in Task 5 resulted in mixed results, even with data compiled from similar or nearby sites. Data parameters from the differing sources vary according to the network objectives, physical obstructions, QA/QC, agricultural/siting representation and instrumentation used. The comparisons also illustrate that data conversions can be difficult given that all sensor characterization information are not published or accommodate network data. Thus, the user is left to determine through deduction experience and as to the probable characterization based on deductive calculations or conversions. In some cases, conversion round off errors exceeds the Task 3 limits.

While good agreement was found to exist in some network based data parameters, the average comparison differences determined in Task 5 generally exceed the Task 3 sensitivity limits and thus would potentially result in unacceptable computational accuracy. Given the data sensitivity results of Task 3, it is apparent that data parameters used without validation and characterization may not be appropriate for use in computing accurate and representative reference ET.

Task 6

Communicate results and provide recommendations regarding identified areas, instrumentation and methods of computation.

Methodology and Results

The methodology used to communicate these results to date has been by dissemination through three seminar/workshop events held in three differing regions of the state. These events were scheduled near the end of the project when most of the data had been compiled and analyzed, but not finalized.

The first event was held in Austin at the Texas Water Development Board headquarters on 21 July 2010 and presented to the Agricultural Water Conservation project leadership. The second event was presented at the USDA-ARS Conservation and Production facility at Bushland on 26 August 2010 and was attended by researchers and groundwater district personnel. The third event was hosted on 13 September 2010 by the Texas Water Resources Institute on the campus of Texas A&M University in College Station and was well attended by state ET network personnel, graduate students, spatial sciences personnel and a TWDB project representative.

There is a vast array of data sources available, but not all sources maintain high quality or standards of data. Personal weather station networks like the Weather Underground take measurements at stations inside cities and towns where buildings can and do significantly alter wind speeds. Wind speeds off by 1 m/s (2.24 mph) result in a 0.25 mm (0.0098 in.) per day error in computed ET values. This 0.25 mm (0.0098 in.) per day error causes an increase of 45.75 mm (1.8 in.) in seasonal reference ET values over a 183 day crop growing season. Effects on crop specific ET values vary depending on the crop and associated crop coefficients. An increase in reference ET will not affect each crop the same. Practical effects of a 2.54 cm (1 inch) increase in reference ET estimates on crop irrigation demand were determined by increasing the seasonal reference ET and using the necessary crop coefficients. Increasing reference ET by 2.54 cm (1 inch) over the growing season will increase irrigation demand estimates for the Texas Panhandle (Region A) by 52.7 million m^3 (42,707 ac-ft). At a pumping cost of \$0.07 per m^3 (\$7.00 per ac-in), this increase in irrigation demand due to sensor error would cost panhandle growers \$3,587,388 in pumping costs alone. Over a 183 day growing season, 0.25 mm (0.01 in.) per day error in reference ET would result in a 45.7 mm (1.8 in.) increase in reference ET over the season. **A 0.25 mm (0.01 in.) per day ETref error can be caused by a 0.5 m/s (1 mph) wind speed error, a 1 degree C (1.8 degree F) air temperature error, a -2 degree C (-3.6 degree F) dew point temperature error, or 25 watts per square meter solar radiation error (nominal daily error of 0.0227%). A combination of less than the aforementioned parameter values could also easily result in an equivalent reference ET increase**. As shown in task 5, these differences can and do occur when using weather station data that are not designed for agricultural ET calculations. In some cases errors resulting from using non-agricultural based weather stations/networks will result in larger ET errors than 0.25 mm (0.0098 in.) per day. Poor or inadequately maintained weather stations can also result in ETref errors due to data drift.

The Texas A&M-Amarillo (TAMA) Region A Model (Marek et al., 2009b) was used to estimate the change in ETc (crop ET) from a change in ETref. The TAMA model methodology utilizes a categorized crop ET based water use approach for estimating regional irrigation demand. Inputs to the TAMA model include acreages provided through the USDA Farm Service Agency (FSA) upon which producer payments are based. The TAMA model requires county-by-county input data regarding crop ET, a term referred to as a “grower factor” (which represents the amount of water pumped and includes the percent of crop ET generally applied by producers using all irrigation system types and associated system application efficiencies), rainfall, soil water type and holding capacity, and seasonal soil profile moisture used per crop planted. The grower factor could be labeled as a “pumpage factor” within Region A representing the amount of water pumped as compared to the ETc demand.

The TAMA model is based on the crop water use equation as follows:

$$ETc*P_T = IRR_C + ER + SSM_D \quad (2)$$

where:

ETc = Crop evapotranspiration (or crop water use) for maximum production potential, in.,

P_T = Grower factor which represents a fraction of the crop evapotranspiration pumped on a crops’ seasonal basis and includes all irrigation systems and associated efficiencies (can be more or less than 1.0 reference crop ET, ETc),

IRR_C = Irrigation applied on a seasonal basis to a crop, in),

ER = Effective rainfall computed from seasonal rainfall occurring during the crop season, in., and

SSM_D = Seasonal soil moisture depletion used in crop production which is extracted from the soil profile during the respective growing season, in.

Rearranging and solving for IRR_C yields:

$$IRR_C = ETc * P_T - ER - SSM_D \quad (3)$$

The summary equation for all categorized crops grown per county is:

$$IRR_{CTY} = \sum_{1}^{n} (IRR_C / 12 * A_C) \quad (4)$$

where:

n = Number of categorized crops of interest per county, and

IRR_{CTY} = Total quantity of irrigation volume applied (or pumped) to the crops grown within a county in a given year or season, ac-ft, and

A_C = Acreage of crop c in a given county, acres.

Similarly, the summary equation for the counties within a region is:

$$IRR_{REG} = \sum_{1}^{n} IRR_{CTY} \quad (5)$$

where:

IRR_{REG} = Total quantity of irrigation volume applied (or pumped) to crops grown within a region in a given year or crop season, ac-ft.

Crop ET data were utilized from the North Plains ET network (Howell, 1998; Marek et al., 1998) as it relates to Region A counties using the ASCE Standardized Reference ET Equation (Allen et al., 2005). The NPET network (NPET, 2009) uses a well-watered grass reference for reference ET. Crop ET data are specifically available for eight of the 21 counties in Region A. Values for the remainder of the counties were computed using a correlation matrix assigning relative representation of weather stations for counties according to attributes of elevation, longitude, and latitude considering known cropping differences of particular counties. A portion of the correlation matrix indicating attribution used in the computations is presented in table 6. Crop season and effective rainfall season periods used in Region A per crop are presented in table 7.

Table 6. Selected meteorological station correlation (proportioning) matrix identifying station attribution used in computing county crop ET values in Region A.

NPET Meteorological Station	Dallam	Hartley	Hansford	Sherman
Dalhart	1.00	0.40	-	0.20
Dimmitt	-	-	-	-
Etter	-	0.40	-	0.60
JBF	-	0.20	-	-
Morse	-	-	0.50	0.20
Perryton	-	-	0.50	-
Wellington	-	-	-	-
White Deer	-	-	-	-

Another significant concern is that of effective rainfall which is addressed by using a modified procedure based upon the USDA Natural Resource Conservation Service (NRCS) method (N.E.H., 1993). Long-term monthly quadrangle rainfall data from the Texas Water Development Board website (TWDB, 2009) is utilized to update and calculate the respective seasonal crop rainfall. This is desired given the spatial representation error of single point rainfall sites

The next model variable required for the water use calculations is an estimation of the “grower factor” associated with each respective crop by producers within Region A. As with previous water planning estimates, data were obtained and analyzed from ancillary research/extension/producer projects that had been conducted within Region A and from comparative parts of Region O. This information was compiled from over 100 specific crop irrigation and production field demonstrations with over 70 cooperating growers in 16 Panhandle counties (New, 2008). These irrigated fields were monitored in terms of water applied (pumped volume) per crop. The resulting irrigation application information is used in equation 3 and is included in the last column of table 8. In addition, over 21 producers' fields were monitored for irrigation applied and used from the production area surrounding the North Plains Research Field (NPRF) in Moore County.

Table 7. Seasonal periods and crop categories used in effective rainfall computations, Region A.

Crop	Growing Season Used in Crop ET Computations	Season Used in Effective Rainfall (ER) Computations	Number of Months Used in ER Calculations
Corn	April 15 - October 15	April 15- August 15	4
Cotton	May 15-October 15	May 15-October 15	5
Grain Sorghum	May 15-October 15	May 15-October 15	5
Hay	April 1-November 1	April 1-November 1	7
Pasture & Other	April 1-November 1	April 1-November 1	7
Peanuts	May 1-November 1	May 1-November 1	6
Soybeans	June 1-November 1	June 1-November 1	5
Wheat	October 1-July 1	October 1-July 1	9
Alfalfa	April 1-November 1	April 1-November 1	7
Forage Sorghum	May 15-September 15	May 15- September 15	4
Sunflowers	May 15-October 15	May 15-October 15	5

Table 8. Average differential seasonal soil moisture and NPET crop ET percentage used in computations per crop category in Region A.

Crop	Differential Seasonal Soil Moisture (SSM), (inches)	Percent of NPET Crop ET Applied by Producers
Corn	2.41	0.86
Cotton	4.22	0.91
Grain Sorghum	3.62	0.84
Hay	1.50	0.95
Pasture and Other	2.50	0.80
Peanuts	2.20	1.35
Soybeans	3.11	0.91
Wheat	3.84	0.79
Alfalfa	1.50	0.95
Forage Sorghum	3.62	0.84
Sunflowers	4.22	0.91

Differential soil profile moisture was assumed to be generally available to each crop at a level of 50 percent per respective crop within Region A. This is commonly referred as the Managed Available Depletion (MAD - Marek, 2009a). The respective available soil profile water quantities used in the model calculations are included in table 8.

Water use by crop was then multiplied by the harvested irrigated acreage (hia) in each respective county to attain the harvested crop irrigation demand estimates (harvested irrigated acreage equals the planted irrigated acreage minus the hailed out irrigated acreage). In addition, the hailed out crop water use was added to the harvested irrigated crop water use to obtain the total water use per crop per county. Hailed out crop water use per county was estimated at 50 percent of the normal full season crop water use value.

The TAMA model (see figure 57 snapshot) is a large, complex spreadsheet developed to document current and forecasted agricultural water demand for the Texas Panhandle. Independent validation assessments of the model have agreed very well with recorded groundwater district well levels and water meter records. This spreadsheet predicts water demand trends through the year 2060. This model is underpinned by accurate crop ET estimates, and it applies several factors to accurately estimate irrigation demand for the entire region. In summary, the factors used in the model include crop type, planted irrigated acres, crop ET, effective rainfall, stored soil moisture and a grower based systems application factor. The method behind this model involves using accurate and representative meteorological data to calculate reference ET, which is then multiplied by a crop coefficient for each crop to determine crop specific ET values. Crop coefficients were derived using the large weighing lysimeters at the USDA-ARS research facility at Bushland, Texas. Seasonal crop soil moisture and effective rainfall is determined using a modified algorithm and both are subtracted from crop ET to give the irrigation demand for a specific crop. The irrigation demand is then multiplied by the planted irrigated acres to provide the total irrigation water demand for a specific crop within a county. The model is currently run for 11 crops typically grown in the 21 counties of the Texas Panhandle. County irrigation demands can then be summed to yield the total regional irrigation demand for the Panhandle (see equation 5). The 21 counties in the region include Armstrong, Carson, Childress, Collingsworth, Dallam, Donley, Gray, Hall, Hansford, Hartley, Hemphill, Hutchinson, Lipscomb, Moore, Ochiltree, Oldham, Potter, Randall, Roberts, Sherman and

Wheeler. The 11 crops typically grown in these counties include alfalfa, corn, cotton, hay, pasture, peanuts, sorghum, forage sorghum, soybeans, sunflowers and wheat. While all crop categories are attributed to each county, not all counties have irrigated acreages for each crop.

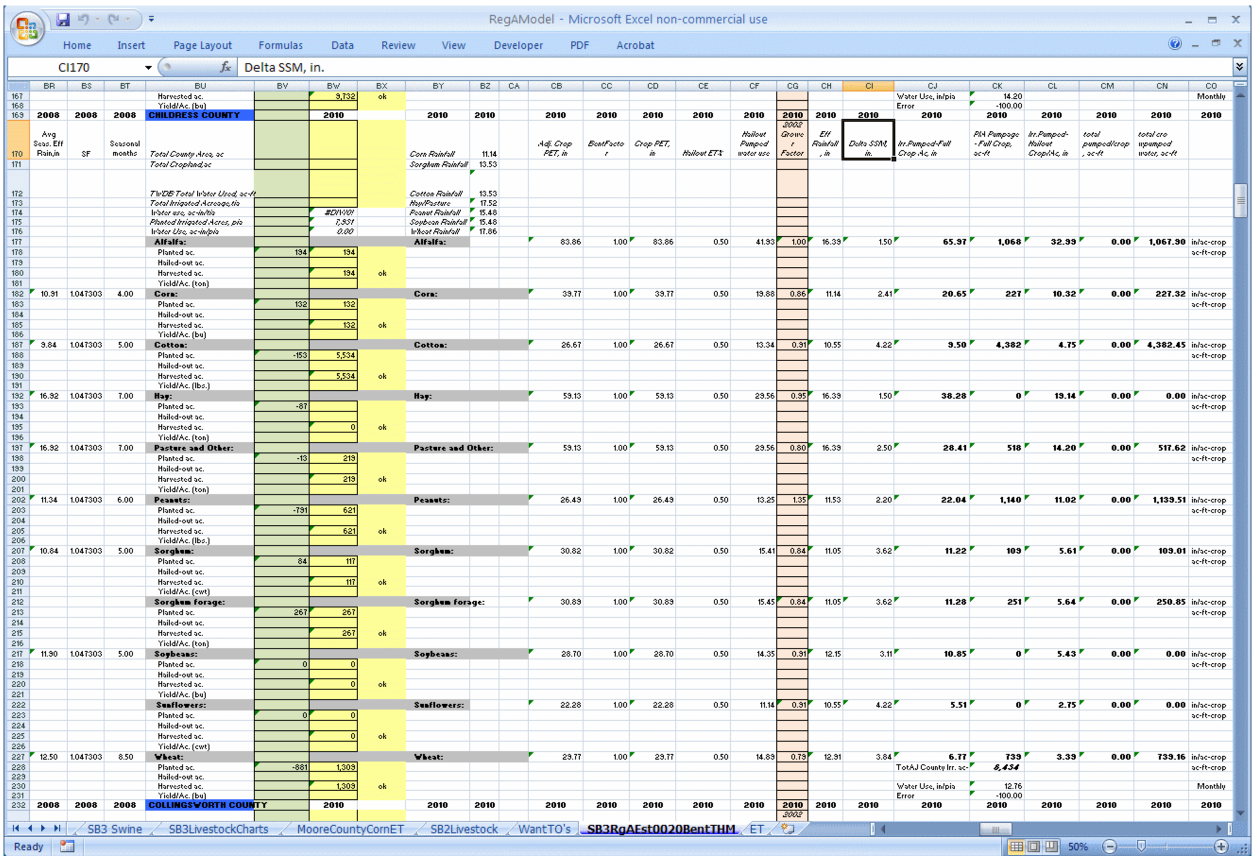


Figure 57. Screenshot (partial) of a single county computations in the TAMA irrigation estimation demand model for Region A. (Source: Marek et al., 2009b).

Looking at corn specifically since it has the highest irrigation water demand in Region A (see Figure 58), the growing season spans from April 15 to October 15, which is a length of 183 days. **ETos calculations off by only 0.14 mm (0.0055 in.) per day would cause an error of 2.5 cm**

(1 in.) accumulated over the summer growing season. Recall that ET values are disseminated daily to producers at only the 0.01 inch level since most producers cannot control irrigation applications at or beyond that level of precision.

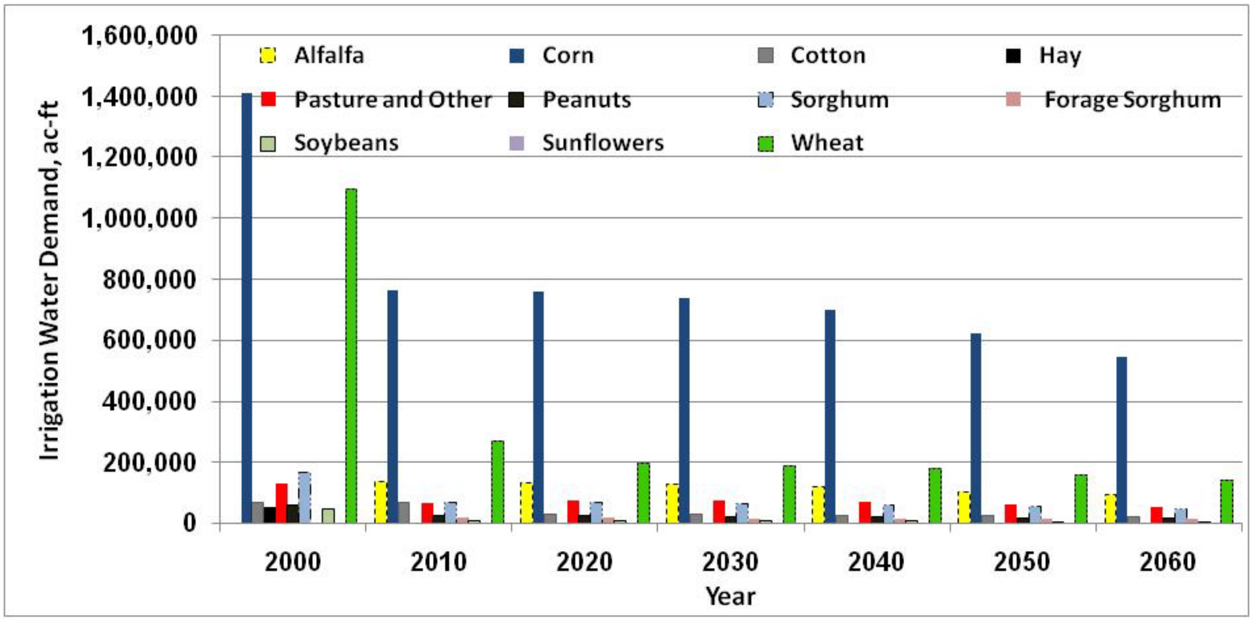


Figure 58. Estimated irrigation demand by crop for Region A. (Source: Marek et al., 2009).

Dallam County (based on 2010 TAMA model data year), irrigates 50,212 hectares (124,076 acres) of corn. This accounts for 53% of irrigated cropland in Dallam County. The normal irrigation demand for the county per year for this crop is 237.99 million m^3 (192,938 ac-ft). The pumping cost (assuming $0.07/$m^3$ or $7/ac-in) for this crop is $16,206,855 each season. If seasonal ET values for corn were erroneously increased by 25 mm (1 in.) the irrigation demand would increase by 9.24 million m^3 (7,493 ac-ft) to 247.2 million m^3 (200,432 ac-ft) for the county. This 25 mm (1 in.) error would cause a total pumping cost increase of $629,412 or $2.05 per hectare ($5.07 per acre). This increase is for Dallam County alone.

Moore County is another major corn acreage county and irrigates 22,958 hectares (56,732 acres) of corn each year, on average. The water applied for this county is 105 million m^3 (85,167 ac-ft), with a pumping cost of $7,154,090. This crop accounts for 40% of the irrigated acres in Moore County. The average seasonal ET for corn in Moore County is 92.6 cm (36.47 in.). If this value is increased by 2.5 cm (1 in.) to 95.2 cm (37.47 in.), irrigation demand would increase by 4.12 million m^3 (3,338 ac-ft). This is a 2.7% increase in ETref causing a 3.9% increase in irrigation demand, based upon crop ET. The cost of the 2.5 cm (1 in.) error is $280,461 or $1.99 per hectare ($4.91 per acre).

For the mix of crops for the entire Texas Panhandle in Region A, **an increase of 0.14mm (0.0055 in.) in daily crop ET would cause an increase in regional irrigation demand of 94 million m^3 (76,247 ac-ft or 24,764,448,000 gallons). The cost of pumping an additional 94 million m^3 (76,247 ac-ft) of water is $6,404,748 annually.** For comparison, the city of Houston with a population of 2,257,926, uses 1.2 million m^3 (970 ac-ft) per day for municipal use (http://www.city-data.com/city/Houston-Texas.html). The amount of water from a 2.5 cm (1 in.) over application of irrigation in Region A could supply the equivalent municipal water for Houston for approximately 2.5 months. Over the Texas Panhandle Region A crop area, a 3.24% increase in crop ET produces a 5.3% increase in irrigation demand. (The reason the relationship is not proportional is due to the mix of crops within Region A with each crop having a differing ET requirement.) Conversely, an underestimate of 2.5 cm (1 in.) of ET demand (i.e. crop water required and or applied) "saves" 92.6 million m^3 (75,130 ac-ft) of water and costs producers production potential. Figure 59 represents the generalized irrigation demand impact of ET errors on a regional basis using the TAMA irrigation demand model. It is readily seen that even a minor ET difference on a regional scale has a significant amount of irrigation demand impact along with the associated cost of pumping. Similarly, if crop ET and irrigation demand are underestimated (reduced) by erroneous ET computations due to incorrect input parameter data, the loss of productivity by producers has fiscal consequence as well.

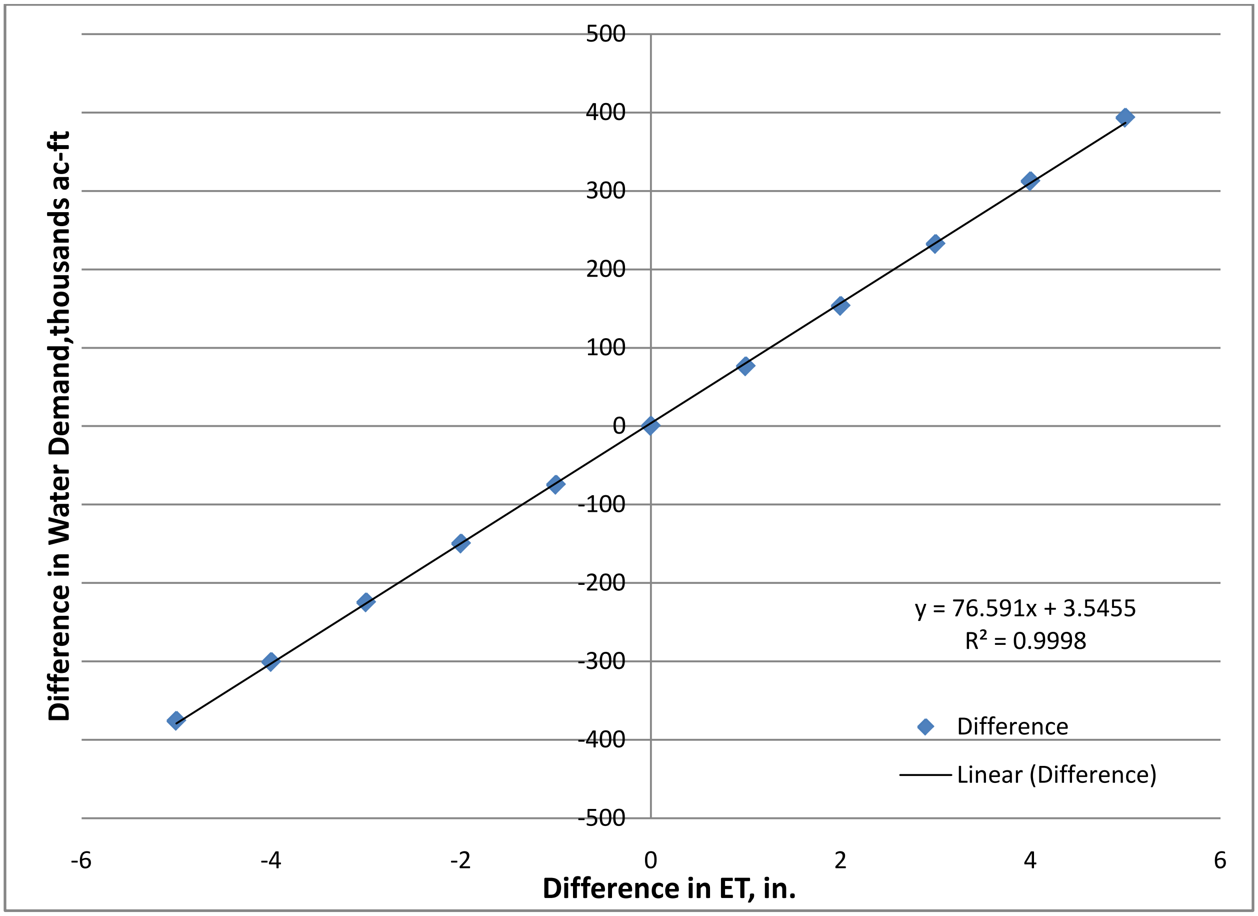


Figure 59. Estimated irrigation demand per ET error relationship for Region A. (Source: Marek et al., 2009b).

Project Conclusions

In the course of this study a total of 24 weather station networks were identified and evaluated for data sourcing within Texas (see table 9). Of these 24 networks, 10 recorded the four necessary parameters for ET calculation; six networks recorded three of the parameters, but did not record solar radiation, and eight networks were considered not viable for ET computation purposes.

Table 9. Table of network name, acronym, purpose and suitability.

Network Name	Acronym	Designed Purpose	ET Suitability
Texas ET Network	TXET	Agriculture	All 4 parameters
Texas High Plains ET Network	TXHPET	Agriculture	All 4 parameters
Crop Weather Program	CWP	Agriculture	All 4 parameters
West Texas Mesonet	WTM	Wind Energy	All 4 parameters
MesoWest/ROMAN	MesoWest	Fire Weather Monitoring	All 4 parameters*
Desert Research Institute	DRI	Fire Weather Monitoring	All 4 parameters
Weather Underground	WU	General Weather Information	All 4 parameters*
Texas AgriLife Center at Overton	TARO	Agriculture	All 4 parameters
New Mexico Climate Center	NMCC	Agriculture	All 4 parameters
Iowa Envionmental Mesonet	IEM	Environmental Monitoring	Missing solar radiation
KVII SchoolNet	KVII	General Weather Information	Missing solar radiation
National Weather Service	NWS	Weather Monitoring and Climatology	Missing solar radiation
National Climatic Data Center	NCDC	Climatology	Missing solar radiation
Midsouth Weather Network	MSWN	General Weather Information	Missing solar radiation
KVIA Weathernet Lab	KVIAWL	General Weather Information	Missing solar radiation
Community Collaborative Rain, Hail, and Snow Network	CoCoRAHS	Precipitation Information	Not viable for ET calculation
WeatherBug	WBN	General Weather Information	Not viable for ET calculation

Bureau of Reclamation	BORHN	Surface Water Monitoring	Not viable for ET calculation
Integrated Agricultural Information and management System	iAIMS	Agriculture and Climatology	Not viable for ET calculation
USDA Weekly Weather and Crop Bulletin	USDAWWCB	Agriculture	Not viable for ET calculation
Lower Colorado River Authority	LCRAN	Surface Water Monitoring	Not viable for ET calculation
Texas Coastal Ocean Observation Network	TCOON	Ocean Water Monitoring	Not viable for ET calculation
Texas Commission on Environmental Quality	TCEQHPWD	Environmental Monitoring	Not viable for ET calculation
US Historical Climatology Network	USHCN	Climatology	Not viable for ET calculation

*not all network stations record all 4 necessary parameters for computation of reference ET.

Investigation indicated that QA/QC procedures varied widely among the networks and data sources, with procedures ranging from completely automated, to only visual inspection to none (or N/A). There appeared to be no uniform standards applied by the majority of networks, and data clearinghouse sites adhered to no obvious QA/QC protocols. These clearinghouse type sites provide data, but it is entirely up to the user to determine the quality or suitability of use of these data, particularly for any agricultural applications.

The sensitivity of ET calculations to data parameters from weather stations was determined to vary seasonally. It was determined and illustrated that wind speed, air temperature, solar radiation and dew point temperature significantly affect ET computations (described in task 3). It was also determined computationally that ETos was more affected than ETrs by inaccurate data or errors. Data error impacts on reference ET are at least two times higher during the summer cropping season than during the other seasons. Based on the sensitivity analysis, relative importance of data in order of impact on ETref computation are wind speed (highest impact), air temperature, solar radiation and dew point temperature (lowest impact). In the cooler seasons of the year, air temperature becomes more influential than wind speed but both still have greater impact than solar radiation and dew point temperature.

Analysis of the various solar radiation sensor data indicates that the sensors drift differently for each model. No obvious relationship with time, U.S. region or stipulated climate was found from this analysis. It was determined that the most commonly used solar radiation sensor for agricultural ET networks exhibited the lowest amount of drift with time as compared to other sensors models. From the data analyzed, a 2 year recalibration schedule is recommended.

Data comparison of the different weather networks with stations sited in similar locations (paired data sources) indicated that they do record differing parameter values. Different networks use different sensors, and many are at different heights than typically required for standards set for agricultural ET data networks. Seemingly small conversion and rounding errors from the data can translate into relatively large volumes in irrigation demand and can have significant impact on water resources projected demands on a regional basis.

Table 10 contains the recommended accuracy of various sensors required in agricultural networks and for computation of ETref.

Table 10. Recommended accuracy of sensor data for agricultural based reference ET computations. (Source: ASABE EP505).

Sensor /Parameter	Accuracy desired	Acceptable Range
Air temperature	± 0.3 ^{o}C	-
Relative humidity	± 3 %	±5 %
Wind speed	± 0.3 m/s	-
Solar radiation	± 3 %	±5 %

Interviews with ET network managers in Texas and other states/regions and losses of entire ET networks in Texas in recent years due to funding and staffing issues indicate that ET networks are at risk from programmatic, infrastructure and data quality/reliability/accessibility/support standpoints. The capabilities, willingness and motivation of these professionals to provide ET data and other meteorological data in support of research programs and other applications for public benefit are noteworthy.

It should be indicated that several ET networks in Texas have ceased operations to date. Losses of the PIN network (Wintergarden area), the San Angelo network and parts of the TXHPET network have occurred. As of September 1, 2010, the TXHPET network exhausted financial resources resulting in the discontinuation of public access to accurate and agriculturally representative reference and crop based ET. Limited grant funds are currently supporting only contracted research projects at a required level of service. After December 31, 2010, many TXHPET network stations will be fully decommissioned and only agency approved, project specific research site stations are planned for the future. The TXHPET network managers fully recognize and regret the void and impact this action presents in one of the most heavily irrigated and agriculturally progressive regions of Texas; however, it has become necessary in these economically challenging times. Suggestions on how to potentially address the issue and data loss are included in the following recommendation section.

Recommendations

Agricultural based data for computation of reference ET should be validated before use. Non-agricultural based data sources especially should be adequately researched and tested for QA/QC implementation before use in ET calculations. Weather station network personnel should understand the equipment, sensors, calibration, importance of appropriate siting, effects of microclimate on data validity, importance of data quality and standardization. Data and ET calculation recommendations are addressed by Allen et al. (2005) and ASCE (2009). Weather station equipment, sites, maintenance and data standards are addressed by ASABE Standard ASAE EP505 (ASAE, 2006) which is currently undergoing review and revision. Every attempt should be made to adhere to the current and purposed standards to ensure comparability and compatibility of data. Network personnel should participate in training opportunities that are available from several agencies and organizations, including the Texas A&M University Irrigation Technology Center in College Station, Campbell Scientific, Inc. in Logan, Utah and the U.S. Forest Service, and stay abreast of advances in detection procedures and techniques to check data.

Air temperature sensors should be recalibrated/changed a minimum of annually in arid and semi-arid environments, and preferably during the period prior to the spring planting season. Wind speed sensor bearings should be changed annually unless the sensors are located in harsh environments (such as in blowing dust or sand prone regions) where a twice per year replacement interval should be implemented. Based on the limited solar sensor data available and reviewed, recalibrations on these radiation sensors should be performed every 24 months, but QA/QC checks are still required to monitor for instrumentation drift and value deviations.

Verification of Rs and other sensor outputs should be conducted after maintenance (recalibration or sensor replacement) due to malfunctions or drift.

If data are to be used from other networks or sources, a process of correlation analysis dealing with a minimum time of record period needs to be addressed and developed between an agricultural based and non-agricultural data source. This methodology would allow a “conversion matrix” from non-agricultural sources to compute ETref for agricultural applications and would entail much more data mining and analysis than conducted in this project. Even after development, there would be some statistical error in conversion but hopefully it would be minimized and acceptable for use where there are no other viable ET network source data available.

Meteorological parameters (including units) and reference ET estimates should be maintained on a statewide basis, particularly for the irrigated regions since irrigated agriculture consumes such a large portion of the water resources in Texas. These data are necessary for ground truthing in research, for regional water planning purposes and for district-level water resource allocations (permitting) as well as for farm-level irrigation planning, scheduling and management. ET networks should be supported through adequate and sustainable means to reduce risks associated with losses of short term grant funding and loss of faculty/managers and other support staff. This risk should be taken seriously, as interruptions in service and loss of infrastructure results in losses of data that are not easily recoverable. Bringing systems back online after such interruptions is ultimately more expensive than properly maintaining systems/databases on an ongoing basis.

A statewide ET data source should be established with stable and sufficient funding provided to support the necessary infrastructure, operations and staffing needed to ensure data integrity. A mechanism or contract for data network support needs to be developed and agreed upon by the participating members, and the TWDB, as the state's water agency, should possibly consider possession of the funding and coordination responsibilities. Additionally, a statewide database of acceptable, documented and maintained data and sources should be electronically warehoused and made readily available for use in research, education and water planning. It would appear that possibly the Texas Natural Resources Information System (TNRIS), the TWDB clearinghouse for natural resources and GIS data, would possibly be the ideal warehouse location for such data. Given the fiscal shortfall in the current state budget, this is a challenging task but one that should be addressed for the future of the citizens of Texas.

Project Based Water Savings

Although this project was of a research nature and not directly related to any field implementation or demonstration projects, the results of this data analysis have a profound impact on the estimations of reference ET and crop water use, particularly in regards to irrigation demand estimates for several large, heavily irrigated regions of the state such as the northern and southern High Plains, the Wintergarden area and the Gulf Coast regions of Texas. As stated previously, **a 1 inch error increase in seasonal irrigation crop ET demand in the Texas Panhandle region alone could result in effectively "wasting" over 51.8 million m^3 (42,000 ac-ft or 13.7 billion gallons) of groundwater resources annually solely because of data errors.** Thus, this study clearly demonstrates that accurate and representative ET data are needed for efficient use of Texas water resources, particularly in the High Plains region where the groundwater is established to be a 10,000 year old resource and is heavily mined (pumpage greatly exceeds recharge). It has been consistently estimated from Region A and Wintergarden producer based data in the last decade that ET networks, when properly operated, maintained and implemented with a sound education/outreach program have reduced seasonally pumped water amounts by growers by 5 cm (2 inches) per year per acre without the loss of crop yield. **That amount of water savings based on the regional acreage in Region A has generally saved producers 18 million dollars annually in energy pumping costs alone.**

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Technical Nomenclature

ASABE

American Society of Agricultural and Biological Engineers

ASABE Standard ASAE EP505

American Society of Agricultural and Biological Engineers standard dealing with weather station guidelines for siting, instrumentation, parameters, output intervals and other associated factors for representative agricultural data acquisition.

ASCE-EWRI

American Society of Civil Engineers – Environmental Water Resources Institute. EWRI is a specialty institute of ASCE dealing principally with ET, irrigation and on-farm issues.

ET Task Committee

A designated task committee of nationally based scientists and engineers serving to address ET, irrigation, hydrology and remote sensing issues.

NPET

North Plains ET Network is a network of weather stations maintained by Texas AgriLife Research at Amarillo with the purpose of providing ET and weather data, along with DSS tools, to growers and researchers in the Texas North Plains. The NPET network is also a part of the TXHPET network.

Penman-Monteith ET

ET equation that requires daily mean temperature, wind speed, relative humidity, and solar radiation to predict net evapotranspiration.

WERA 202

Western Education and Research Administrators national steering committee on Climatic Data Application in Irrigation Scheduling and Water Conservation.

Appendices

Appendix A – ASABE EP505

ASAE EP505 APR2004
Measurement and Reporting Practices for Automatic Agricultural Weather Stations

American Society of
Agricultural and Biological Engineers

STANDARD

ASABE is a professional and technical organization, of members worldwide, who are dedicated to advancement of engineering applicable to agricultural, food, and biological systems. ASABE Standards are consensus documents developed and adopted by the American Society of Agricultural and Biological Engineers to meet standardization needs within the scope of the Society; principally agricultural field equipment, farmstead equipment, structures, soil and water resource management, turf and landscape equipment, forest engineering, food and process engineering, electric power applications, plant and animal environment, and waste management.

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Measurement and Reporting Practices for Automatic Agricultural Weather Stations

Developed by the ASAE SW-244 Irrigation Management Subcommittee; approved by the ASAE Soil and Water Division Standards Committee April 2004.

1 Purpose and scope

1.1 Purpose: The purpose of this Engineering Practice is to establish minimum recommendations for measurement, reporting, siting, operation, maintenance, and data management procedures for automatic agricultural weather stations. Additionally, these recommended procedures are intended to assist in the planning of automatic agricultural weather station installation and operation.

1.2 Scope: This Engineering Practice applies to automatic weather stations installed individually, or as part of a network of stations, for the measurement and reporting of specific weather variables in agricultural environments. This Engineering Practice also addresses a recommended core set of measurements and general siting considerations for agricultural weather stations. It is recognized that special purpose agricultural weather stations may deviate from the recommendations herein, particularly with respect to sensor deployment and station siting conditions. This Engineering Practice does not specifically address these special purpose stations.

2 Normative references

The following standard contains provisions that, through reference in this text, constitute provisions of this Engineering Practice. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this Engineering Practice are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Standards organizations maintain registers of currently valid standards.

ASAE S526.2 JAN01, *Soil and Water Terminology.*

3 Definitions

3.1 Definitions. For the purpose of this Engineering Practice only, the following definitions are defined herein. Additional terminology is defined in ASAE Standard S526, Soil and Water Terminology.

3.2 adiabatic lapse rate. The decrease in temperature of a parcel of air with height above the surface when lifted in elevation adiabatically, that is, without the addition or withdrawal of heat from the surrounding air. The adiabatic lapse rate of dry air is about 1°C/100 m.

3.3 anemometer: Instrument for measuring the speed of the wind.

3.4 atmospheric (barometric) pressure: The pressure exerted by the weight of air (dry air and water vapor mixture) above a given point.

3.5 automatic agricultural weather station: A stand-alone set of equipment designed to automatically measure and record agriculturally significant weather variables, as specified in clause 4, for agricultural purposes. The station is based on an electronic data logger and includes associated sensing devices, power supplies, environmental enclosures, and support structures, normally operated on a year-round basis at a fixed location and it may be part of a network of similar stations. It collects data at a specified sampling interval(s), stores intermediate measurements in memory, processes summary values at a specified reporting interval, and stores the summary values in memory. Finally, it incorporates some means of data telemetry for access to, or transfer of, summary values, typically on a near-real time basis, to a central location for more general processing, long-term storage and dissemination, or to alternative on-site exchangeable storage media.

3.6 climate day: A 24-hour period (e.g., midnight to midnight, 8 am to 8 am, local standard time) for which a statistical summary of the measured weather values is prepared (means, maximums, minimums, totals, etc.)

3.7 data logger: An electronic, microprocessor-based device that can be programmed to make measurements of specific sensors, to process the measurements, and to store intermediate measurements and summary data values.

3.8 dew-point temperature: The temperature to which moist air at a specific barometric pressure, relative humidity, and temperature must be cooled to reach moisture saturation.

3.9 dry-bulb temperature: Ambient air temperature.

3.10 evaporation: The process by which a liquid changes into a gas.

3.11 fetch: The extent of homogeneous area surrounding a given point.

3.12 fully adjusted layer: Approximately the lowest 10% of the internal boundary layer that is in complete equilibrium with new surface boundary conditions caused by a transition in surface conditions.

3.13 internal boundary layer: The layer of air downwind of a transition in surface characteristics such as surface roughness; its thickness increases with distance downwind, or down fetch.

3.14 psychrometer: Instrument used to measure the water vapor content of the air by measuring the wet-bulb and dry-bulb temperature of the air.

3.15 radiation shield: A device used for housing air temperature sensors that reduces the temperature effects of radiation on the sensor.

3.16 resistance temperature detector: A length of pure metal (wire), carefully wound in a stress free form, that increases in resistance as the temperature of the metal (wire) increases.

3.17 sampling interval: The time interval between successive measurements of a sensor, or sensors, by a data logger.

3.18 saturation vapor pressure: The partial pressure exerted by water vapor when it is in equilibrium with a plane surface of pure water.

3.19 sensor: A device that provides a measurable signal output in response to a physical stimulus or variable.

3.20 soil heat flux: The flow of heat energy per unit cross-sectional area into, or out of, the soil.

3.21 solar radiation (irradiance) (direct, diffuse, global, longwave, net, shortwave): Direct solar radiation is the radiation coming from the solid angle of the sun's disc; irradiance is the property that is measured. Diffuse, or sky radiation, is downward, scattered and reflected solar radiation coming from the whole hemisphere. Global radiation is the sum of direct and diffuse solar radiation. Longwave radiation is the infrared energy emitted by the earth and the atmosphere. Net radiation is the sum of net shortwave radiation and net longwave radiation. Shortwave radiation is the radiant energy emitted from the sun at wavelengths less than 4 microns.

3.22 surface roughness: Aerodynamic roughness of a surface; a parameter affecting the downward transport of horizontal momentum from airflow to a surface.

3.23 telemetry: The transmission of data collected at a remote location to a central station, using one or more means of communication.

3.24 thermal stability: A concept describing the variation of temperature with elevation in the atmosphere. When the actual air temperature decreases with height above the surface at a rate greater than the dry adiabatic lapse rate (about 1° C/100 m), the atmosphere is unstable, the temperature is termed a lapse profile, air is buoyant, and turbulence or mixing is enhanced. When the actual air temperature decreases with height above the surface at a rate less than the dry adiabatic lapse rate, the atmosphere is stable, the temperature profile is termed an inversion, air tends to hold its position vertically, and turbulence or mixing is suppressed. When the actual air temperature profile equals the dry adiabatic lapse rate, the atmosphere is neutral.

3.25 thermistor: An electrical resistance device for measuring temperature that exhibits rapid and large changes in resistance for relatively small changes in temperature.

3.26 thermocouple: A device consisting of two dissimilar metals joined together at their end that produces a thermoelectric voltage proportional to the temperature difference between the two junctions.

3.27 time constant: The time required for an instrument to make a 63.2 percent adjustment to new environmental conditions, in which the measurement system is a linear, first-order, time-invariant, step function input. This percentage is equal to the quantity (1-1/e) where e is the base of the natural logarithm, 2.7182.

3.28 vapor pressure (actual): The pressure exerted by the water vapor molecules in air at a given temperature.

3.29 wet-bulb temperature: The temperature to which moist air can be cooled adiabatically (without any gain or loss of heat) by evaporation.

3.30 wind speed: Horizontal movement of air in distance per unit time.

3.31 wind direction: The direction from which air is moving.

3.32 wind vane: Instrument used to indicate wind direction.

3.33 zero plane displacement: The mean level, or height, at which momentum is absorbed by individual elements on a surface, e.g., plant leaves.

4 Measurements

4.1 Variables

4.1.1 Core variables. The recommended core variable set to be measured on an agricultural weather station should include solar radiation, air temperature, relative humidity, wind speed, wind direction, rainfall (total and intensity), and soil temperature (Table 1).

4.1.2 Derived variables. Variables derived from the core set of measured variables and applicable formulae for their derivation should include (see Table 1):

4.1.2.1 Saturation vapor pressure. Saturation vapor pressure should be calculated and logged with each sampling of air temperature and may be determined using an equation such as that of Tetens (1930) or Murray (1967):

$$e^0 = \exp[(16.78T - 117)/(T+237.3)]$$

Allen et al. (1994) give the Tetens (1930) equation as:

$$e^0 = 0.611\ \mathrm{EXP}\ [17.27\ T/(T+237.3)]$$

and Allen et al. (1998) give the Tetens (1930) equation as:

$$e^0 = 0.6108\ \mathrm{EXP}\ [17.27\ T/(T+237.3)]$$

where:

e^0 = saturation vapor pressure (kPa)

T = air temperature (°C)

.

Lowe (1977) gives an equation for saturation vapor pressure as,

$$e^0 = a_0+T(a_1+T(a_2+T(a_3+T(a_4+T(a_5+a_6T)))))$$

where:

e^0 = saturation vapor pressure (kPa)
T = air temperature (K)
a_0 = 698.450 529 4
a_1 = −18.890 393 10
a_2 = 0.213.335 767 5
a_3 = $-1.288\ 580\ 973\times10^{-3}$
a_4 = $4.393\ 587\ 233\times10^{-6}$
a_5 = $-8.023\ 923\ 082\times10^{-9}$
a_6 = $6.136\ 820\ 929\times10^{-12}$.

Note that a different formula for saturation vapor pressure with respect to an ice surface should be used. The definition of relative humidity requires the use of saturation vapor pressure with respect to a water surface at all temperatures.

4.1.2.2 Actual vapor pressure. Actual vapor pressure of the air should be calculated and logged with each sampling of air temperature and relative humidity, and is determined by:

$$e_a = e^0\ (RH/100)$$

where:

e_a = actual air vapor pressure (kPa)

RH = relative humidity (%).

4.1.2.3 Vapor pressure deficit. Vapor pressure deficit should be calculated and logged with each sampling of air temperature and relative humidity, and computed using:

$$VPD = e^0 - e_a$$

where:

VPD = vapor pressure deficit (kPa).

4.1.2.4 Wind data reduction. Scalar mean wind speed, unit vector mean wind direction, resultant mean wind speed and direction, and standard deviation of wind direction may be computed using raw sampled data values in the following relationships:

$$W = \Sigma(w_i)/n$$

$$\theta_u = \tan^{-1}\ (w_x/w_y)$$

$$w_x = \Sigma(w_i \sin\theta_i)/n$$

$$w_y = \Sigma(w_i \cos\theta_i)/n$$

$$U = (w_x+w_y)^{0.5}$$

$$\theta_1 = \tan^{-1}(w_{x1}/w_{y1})$$

$$w_{x1} = \Sigma(\sin\theta_i)/n$$

$$w_{y1} = \Sigma(\cos\theta_i)/n$$

$$\sigma(\theta_u) = 81(1-U/W)^{0.5}$$

$$\sigma(\theta_1) = \sin^{-1}(\varepsilon)[1+0.1547\varepsilon^3]$$

$$\varepsilon = [1-(w_{x1}{}^2+w_{y1}{}^2)]^{0.5}$$

where:
W = scalar mean horizontal wind speed (ms^{-1})
w_i = sampled wind speed data values (ms^{-1})
n = number of samples
θ_u = resultant mean wind vector direction (degrees)

w_x = speed weighted mean wind vector component in East-West direction
w_y = speed weighted mean wind vector component in North-South direction
θ_i = sampled wind direction data values (degrees)
U = resultant mean wind vector magnitude (ms^{-1})
θ_1 = unit vector mean wind direction (degrees)
w_{x1} = mean unit vector component in East-West direction
w_{y1} = mean unit vector component in North-South direction
$\sigma(\theta_u)$ = standard deviation of wind direction, Campbell Scientific algorithm (CSI, 1987)
$\sigma(\theta_1)$ = standard deviation of wind direction, Yamartino algorithm (US EPA, 1987).
x,y = coordinate system in the horizontal plane with x-axis aligned with East.

4.1.3 Supplemental variables. Supplemental and additional variables which may be measured or derived on an automatic agricultural weather station include: net radiation; photosynthetically active radiation; air temperature, relative humidity, and wind speed at heights other than those specified in Table 1; soil temperature at depths other than those specified in Table 1; soil temperatures under other surface conditions; standard deviation of wind speed (see clause 4.1.2.4); dew-point temperature; soil water content; soil heat flux; leaf wetness; barometric pressure; surface temperature; evaporation (by Class A Pan or atmometry if successfully automated, otherwise evapotranspiration is calculated); solid precipitation (snow fall and snow depth). Suitable algorithms exist for the estimation of some of these variables using the measured standard variable set, e.g., net radiation, soil heat flux, evapotranspiration, photosynthetically active radiation.

4.2 Units. All measured and derived variables should be reported in SI (metric) units. See Table 1 for recommended units for each variable.

4.3 Deployment. Recommended deployment heights and depths for each standard measurement given in clause 4.1 are listed in Table 1. For purposes of reference evapotranspiration computation using a Penman model, daily average wind speed at 2-m height above the surface is required. Daily average wind speed at 2 m may be estimated from the measured data at height z using the following general relationship (Jensen et al., 1990):

$$W_2 = W_z(2/z)^{0.2}$$

where:
W_2 = estimated wind speed at 2-m height (ms^{-1}),
W_z = wind speed (ms^{-1}) measured at height z (m).

Or, to account for measurement surface roughness:

$$W_2 = W_z[\ln((2-d)/z_o)/\ln((z-d)/z_o)]$$

where W_2, W_z, and z are as previously given and:
d = zero plane displacement height of the measurement surface (m),
z_o = surface roughness height for momentum transfer (m).

d and z_o may be approximated as:

$$d = 0.7\ h_c$$

$$z_o = 0.1h_c$$

where:

h_c = vegetation height (m).

4.4 Sampling interval. Recommended data logger sampling intervals for each measurement given in clause 4.1 are listed in Table 1. It is probable the data logger will be programmed to sample at the smallest sampling interval and thus all sensors will be sampled at that rate. The World Meteorological Organization (WMO) standard for wind measurements is a 3-s sampling interval. The Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) has issued a standard method for characterizing surface wind that requires a 3-s sampling interval (OFCM, 1992). When characterization of wind is an important component of the automatic agricultural weather station program, it is advisable to follow the OFCM wind standards. The OFCM standard data output includes additional parameters to those listed in Table 1 for wind speed and direction. Note that a more frequent sampling rate will drain batteries more quickly, making battery maintenance a more important factor for battery-powered stations without solar panels.

4.5 Reporting. Reporting interval and values to be reported for each of the core and derived variables are listed in Table 1. The hourly reporting interval of values specified in Table 1 allows data users to generate summaries for different climate days, i.e., midnight to midnight, 0800 to 0800, etc., as desired. A midnight to midnight daily reporting interval is recommended. Data should always be collected and reported in local standard time.

5 Types of equipment

5.1 Data loggers. A microprocessor-based electronic data logger is the necessary basis of an automatic agricultural weather station. This device must be user-programmable to allow, at a minimum, readings of instruments listed in Table 1 at the recommended sampling intervals listed in Table 1. Additionally the data logger must be capable of intermediate processing of data such as computation of the derived variables listed in clause 4.1.2, storage of intermediate values, computation of the statistical summary values listed in Table 1, and storage of summary values. Finally, the data logger must have appropriate communications interfaces for data transfer to storage media or data telemetry equipment.

5.2 Solar radiation (irradiance) sensors. Total or global solar radiation may be measured with pyranometers or total hemispherical radiometers. Pyranometers may be of the thermopile or photocell types. Instruments should have compensation for temperature dependence. The instrument should have sensitivity across the entire spectral range affecting biological activity. The typical short-wave spectrum is 0.3 to 3 microns.

5.3 Temperature sensors. Air and soil temperature may be measured with thermistors, resistance temperature detectors (RTD), or thermocouples. Thermocouples measure the temperature difference between a measuring junction and reference junction; the reference junction will typically be at a data logger or multiplexer wiring panel, requiring a temperature measurement at the panel. Air temperature sensors must be deployed in a minimum of a naturally-ventilated radiation shield. Soil temperature sensors must be environmentally sealed to prevent moisture penetration and to allow for direct burial in the soil.

5.4 Relative humidity sensors. The most common types of relative humidity sensors used on automated agricultural weather stations measure changes in physical, chemical, or electrical properties of a material upon absorption of water vapor by, or adsorption of water vapor to, the material. These may include strain measurements, or measurements of the change in electrical resistance or capacitance. Psychrometers are generally not used on remote stations due to the high power requirements of the aspirating mechanism and the problem of providing a continuous water supply to the wet-bulb temperature device.

5.5 Wind instruments

5.5.1 Wind speed. Wind speed is typically measured on an automatic weather station using a cup or propeller anemometer; horizontal wind speed is typically the only component measured. Devices may be of switch closure type, optical type, or the type that generates an AC signal or a DC signal.

5.5.2 Wind direction. Wind direction is measured with a wind vane. The measurement will be the direction from which the air is moving. Wind vanes should be aligned relative to true north, i.e., 0 degrees is true north, 90 degrees is east, etc.

5.6 Rain gages

5.6.1 Tipping bucket gages. Tipping bucket rain gages operate on a

Table 1 – Core variable set, units, deployment heights, sampling intervals, and values reported for automatic agricultural weather stations

Variable	Derived variables	Units	Deployment height (m)	Sampling interval (s)	Values reported each hour
Solar radiation	---	W m^{-2}	[1]	≤ 10	average
Air temperature [2]	---	°C	1.5 to 3	≤ 60	average instantaneous max/min
	Sat. vapor pressure	kPa	---	[3]	---
Relative humidity [2]	---	%	co-located with air temperature	≤ 60	average instantaneous max/min
	Vapor pressure	kPa	---	[4]	average
	Vapor pressure deficit	kPa	---	[4]	average
Wind speed [5]	---	m s^{-1}	2 to 3	≤ 10	scalar mean maximum during interval and time of occurrence
Wind direction [6]	---	deg	co-located with wind speed	≤ 10	unit vector or resultant mean magnitude and direction standard deviation
Rainfall [7]	---	mm h^{-1} [8]	≤ 10	[8]	total rate or intensity [8]
Soil temperature [9]	---	°C	−0.10 to −0.20[10]	≤ 60	average instantaneous max/min

Notes for Table 1:

1) Deploy to avoid shading by and reflection from nearby objects. Practical considerations for height include ease of maintenance, i.e., routine cleaning and checking instrument level.
2) Supplemental data, which may be reported, are times of occurrence of maximum and minimum values.
3) Saturation vapor pressure is calculated with each sample of air temperature (see text for equation) and may be reported as supplemental data. See clause 4.1.2.1.
4) Vapor pressure and vapor pressure deficit are calculated with each sample of relative humidity and air temperature. Supplemental data that may be reported are times of occurrence of maximum and minimum values. See clauses 4.1.2.2 and 4.1.2.3.
5) See clause 4.1.2.4. WMO and OFCM standard is 3-second sampling rate for wind speed and direction, see clause 4.4. WMO standard height for wind measurements is 10 m.
6) Azimuth direction referenced to true North. See clause 4.1.2.4 for algorithms for calculating hourly mean wind direction (magnitude and direction) and standard deviation of wind direction from sampled values.
7) Liquid precipitation only.
8) Sampling is event driven for tipping bucket rain gages. To obtain the rainfall rate or intensity, record the time of each tip for tipping bucket gages; for weighing gages, record the total weight and time for each 0.254 mm (0.01 in.) of rainfall to obtain both total rainfall and intensity. Hydrologists recommend a minimum sampling interval of 15 min; 1-min sampling intervals are often used.
9) Measure under bare soil surface conditions. Soil moisture at probe depth should be maintained at levels equivalent to the environment being represented (i.e., irrigated vs. dryland sites).
10) Soil temperature deployment is often dependent on the intended use of the data; the values of −0.10 m and −0.20 m are typical depths of installation.

switch closure principle generating electrical pulses with each tip of a small bucket that receives liquid from a funnel. Knowing the depth represented by each tip and counting the number of tips, the depth of rainfall over a specified time interval can be determined. Rainfall intensity can be determined by recording the time of each tip in addition to counting the tips. Unless heated, tipping buckets are limited to measurement of liquid precipitation.

5.6.2 Weighing gages. Weighing gages weigh and record all forms of precipitation as soon as they fall into the gage. Anti-freeze may be used to avoid ice formation in the bucket and oil may be used to retard evaporation. Weighing gages are sensitive to strong winds, which often cause erroneous readings.

5.7 Data storage/telemetry

5.7.1 On-site data storage. On-site data storage requirements are dependent upon the method and frequency of data retrieval. Data loggers should be equipped with adequate memory to store data for a minimum of several days. Transfer of data to on-site memory or to recording devices (solid state memory, cassette tape, etc.) should occur hourly and daily as per the reporting intervals in Table 1. Frequency of exchange of on-site data storage media is dependent on capacity, data utilization requirements, etc.

5.7.2 Telemetry equipment. Data telemetry to a central computing facility may be accomplished via telephone (standard or cellular) and modem connection, land-based radio frequency telemetry, satellite telemetry, meteor burst technology, etc.

5.8 Other equipment

5.8.1 Station power. Most data loggers operate on direct current (DC) power. Power requirements of the data logger for measurement, and processing and storage of data should be minimal, allowing for extended operation before it becomes necessary to replace batteries. AC power at the weather station site may be used for trickle charging the battery with an appropriate voltage transformer and adequate surge protection. Solar panels may also be used to trickle charge batteries with appropriate voltage regulation. Batteries of the sealed gel-cell type may be housed in the same enclosure as the data logger and telemetry equipment. Wet cell batteries should be housed in a separate enclosure to minimize the risk of hydrogen gas buildup and possible explosion within the data logger enclosure, as well as to avoid corrosion of electronic equipment terminals.

5.8.2 Enclosures. All enclosures should be rainproof. Enclosures housing the data logger should be National Electrical Manufacturer's Association (NEMA) type 4 with a gasket type seal on the door. Ports for sensor leads should be sealed with electrician's putty. Desiccant packs should be kept within the data logger enclosure and maintained according to clause 9.3.5.

5.8.3 Structure. Data logger enclosures, battery enclosures, all sensor mounting arms, etc. should be rigidly attached to the weather station structure. The weather station structure may be a tripod, a free-standing tower, or a guyed tower. The weather station structure should be firmly anchored to the ground and should be equipped with an electrical grounding system connected to an earth ground and a lightning rod. All instruments, the entire tower/structure, and all connections leading to the tower should be connected to a common ground. This ensures that there are no ground loops in the system, where voltage differentials between the instruments and data logger or tower can develop. Sensors not directly mounted on the main station structure should be mounted on their own rigid and anchored structure. Provisions should be made to bring the sensor leads to the data logger in buried moisture-and rodent-proof conduit.

6 Measurement requirement and uncertainty

6.1 General. A fundamental objective of this engineering practice is to define requirements and practices necessary to:

- characterize the uncertainty in measurements obtained;
- obtain measurements of sufficient quality to be useful for the intended agricultural applications or products.

Table 2 – Typical measurement range, resolution, and estimated field accuracy of sensors used on automatic agricultural weather stations

Variable	Range	Resolution Variable	Resolution Digital	Specified accuracy	Estimated field accuracy
Solar Radiation	0 to 1500 W m^{-2}	5 W m^{-2}	(33 μV)	typical: ±3% OR[1] max: ±5% OR	same as specified
Air temperature thermistor (resistance)	−30°C to 50°C	0.1 °C	(1 mV V^{-1})[2]	±0.3°C	aspirated: ±0.5°C unaspirated: +0.5 to 2.5°C −0.5 to −1°C
PRT (resistance)	---	---	(100 μV V^{-1})	±0.2°C±0.15%OR[3] ±0.35° C±0.4%OR[4]	---
Thermocouple	---	---	(4 to 6 μV)	±0.75% of (T_m − T_R)[5] ± T_R error	---
Soil Temperature	---	---	---	---	±0.5 °C
Relative humidity	10 to 100% RH	1% RH	(10 mV)	±3% to ±5% RH	±5% RH
Wind speed (frequency)	0.5 to 40 m s^{-1}	0.5 m s^{-1}	---	±0.3 m s^{-1} or ±2% OR	---
Wind direction (vane)	0 to 360 deg	5 deg	(14 mV V^{-1})	±3 to 5 deg	10 deg
Rainfall	0 to 200 mm h^{-1}	0.25 mm h^{-1}	---	---	−10% at 100 mm h^{-1}

Notes for Table 2:
1) OR: Of Reading
2) Units of mV V^{-1} in the digital resolution column reflect resolution required per volt of excitation to resistance of sensor.
3) Class A
4) Class B
5) Specified accuracy for thermocouples is in terms of T_m and T_R , the measurement and reference temperatures.

The quality of measurements obtained requires a compromise between the cost of instrumentation and maintenance, and the need for long-term operation. Estimates of the measurement uncertainty one can expect using sensors and practices commonly employed in long-term weather station operation, are given in Table 2. Sensitivity analyses of various agricultural applications (ET estimation, crop modeling, pest and disease prediction) to expected measurement uncertainty are required to determine the usefulness of measured variables for such applications. If the level of uncertainty reduces the usefulness of the measurements, additional or tighter specifications for both sensors and practices must be considered.

Flexibility in the choice of sensors and instrumentation by weather station operators is desirable. The intent of this section is to provide guidance on desirable measurement ranges and measurement resolution. The choice of sensors influences the maintenance and calibration schedules needed to maintain a desired level of measurement quality.

Types of sensors commonly used in agricultural and climatic networks are listed in Table 2. A number of other sensor options exist beyond those shown. Higher quality sensors may exist, but the information in Table 2 is intended to assist in the selection of a sensor type capable of obtaining the desired quality of measurement. The minimum acceptable quality of data is in part determined by the measurement capability for a given sensor type. The quality of measurement may differ greatly between sensors of the same type, but from different manufacturers.

6.2 Measurement range. The desired measurement range for an individual variable should be specified or known. Table 2 provides general guidance, however, certain regions of the world may not require ranges as broad as those given for some variables (e.g., air temperature).

6.3 Measurement resolution. Two columns are listed under measurement resolution in Table 2; variable resolution is that needed for the specific application(s) of the data. To avoid ambiguity, the resolution should be specified for an individual measurement as opposed to the time-averaged, recorded value. Values given in Table 2 are suggested initial values for evaluation.

Digital resolution is the resolution required of the measurement electronics for a particular type of sensor signal, in order to obtain the accompanying specified variable resolution. Values given in Table 2 are for information purposes only.

6.4 Accuracy

6.4.1 Manufacturer's specifications. Values shown in Table 2 in the specified accuracy column refer to manufacturer's specified accuracy. In some cases the values reflect a specific manufacturer, and in others, a typical value from a distribution provided by several manufacturers of the same type of sensors. The accuracies should be regarded as representative of bench top environments rather than achievable field operational accuracies. Values given in Table 2 are given for information purposes only.

6.4.2 Operational field accuracy. Values shown in Table 2 are representative of the uncertainty of measurements made under field conditions. The values are provided as first estimates for determining their usefulness for agricultural applications.

7 Documentation

7.1 General. Each automatic agricultural weather station site installation should have a station history document developed and maintained for the duration of the installation. This station history file must be available to all potential users of data collected at the weather station. Station grounds conditions and maintenance; sensor condition, maintenance, calibration, and replacement; etc.; should all be included in the station history file. The station history file is important documentation needed for such activities as investigation of data anomalies, etc. The station history file should contain physical information about the site and surrounding area, information about the array of sensors deployed at the site (clause 7.2), site and sensor maintenance information, sensor calibration data (clause 7.3), and descriptions of electronic data retrieval and storage (archival) formats (clause 7.4).

7.2 Site documentation. Each weather station site should be identified with a unique identification label. Written documentation describing the weather station installation site should be developed and periodically updated. Constant geographic data such as station elevation above mean sea level, latitude and longitude to the nearest 30 seconds of arc, and land slope and aspect should be included.

7.2.1 Site description. Site characteristics to be described include: ground cover characteristics (type and height), soil type, and irrigated or rainfed conditions under the station and in the immediate vicinity (radius out to 200 m) of the station. Terrain features (hills, trees, bodies of water, buildings, etc.) of the surrounding local area (radius out to 5000 m) should be described by distance, height, and sector. Written descriptions of the immediate vicinity of the site and local surrounding area should be supplemented with photographs taken in a minimum of each of 8 coordinate directions (45° sectors), and preferably 12 coordinate directions (30° sectors), several times per year (at least twice during the growing season; beginning and mid-season). Average surface roughness in each sector should be characterized and recorded using the roughness classifications given in Table 3.

General comments about the agriculture (irrigated or rainfed, crop types, growing seasons, etc.) in the region of the station (radius up to 50 km) should be included. Descriptions should include natural and anthropogenic-based changes to the area surrounding the site as a function of time during the calendar year (e.g., cropping patterns, growth cycles, etc.).

7.2.2 Sensor exposure description. Written documentation describing the array of sensors deployed at a site and their deployment characteristics (height, depth, orientation, etc.) should be developed and maintained. Sensors should be described by name of manufacturer, serial number, or other identification number. Dates of installation, maintenance and/or calibration activity (clause 7.3), and removal or replacement should be recorded. All changes in sensor deployment characteristics should be documented when they occur.

7.3 Calibration and maintenance documentation

7.3.1 Calibration. All calibration activities should be recorded on a standard form showing part or sensor name or other identifier, serial number, date, and a checklist of activities performed. Deviations of sensor performance from calibration sensors should be noted, both before and after the calibration. Completed forms should be maintained in at least a paper filing system, and preferably, also in an electronic database file. All calibration records should provide a trace of the sensor or part history, and should be cross-referenced with station/sensor maintenance record keeping.

7.3.2 Maintenance. All maintenance activities, whether scheduled routine maintenance or unscheduled emergency maintenance, should be recorded on a standard form showing station name or other identifier, date of visit, and a checklist of activities performed. Record notes on these forms detailing "as found" and "as left" conditions. The form should also contain a checklist for ensuring the station and data logger are left in proper operational state upon completion of the maintenance visit. Completed forms should be maintained in at least a paper filing system for each station, and preferably, also in an electronic database file. All station/sensor maintenance records should be cross-referenced with all calibration records.

7.4 Data documentation. All data should have written documentation, electronic or otherwise, developed and maintained describing means for data access and retrieval. Additionally all data sets should be accompanied with documentation describing storage (archival) formats (see clause 10).

8 Station siting

8.1 Exposure. Ideally, agricultural weather stations should be sited in level, open terrain representative of the local agricultural environment.

Table 3 – Average surface roughness classification (after Wieringa, 1992)

No.	z_0 (m)	Landscape description
1	0.0002 "Sea"	Open sea or lake (irrespective of the wave size), tidal flat, snow-covered flat plain, featureless desert, tarmac and concrete, with a free fetch of several kilometers.
2	0.005 "Smooth"	Featureless land surface without any noticeable obstacles and with negligible vegetation; e.g., beaches, pack ice without large ridges, morass, and snow-covered or fallow open country.
3	0.03 "Open"	Level country with low vegetation (e.g., grass) and isolated obstacles with separations of at least 50 obstacle heights; e.g., grazing land without windbreaks, heather, moor and tundra, runway area of airports.
4	0.10 "Roughly open"	Cultivated area with regular cover of low crops, or moderately open country with occasional obstacles (e.g., low hedges, single rows of trees, isolated farms) at relative horizontal distances of at least 20 obstacle heights.
5	0.25 "Rough"	Recently-developed "young" landscape with high crops or crops of varying heights, and scattered obstacles (e.g., dense shelterbelts, vineyards) at relative distance of about 15 obstacle heights.
6	0.5 "Very rough"	"Old" cultivated landscape with many rather large obstacle groups (large farms, clumps of forest) separated by open spaces of about 10 obstacle heights. Also low large vegetation with small interspaces, such as bushland, orchards, young densely-planted forest.
7	1.0 "Closed"	Landscape totally and quite regularly covered with similar-size large obstacles, with open spaces comparable to the obstacle heights; e.g., mature regular forests, homogeneous cities or villages.
8	≥ 2 "Chaotic"	Center of large towns with mixture of low-rise and high-rise buildings. Also irregular large forests with many clearings.

Stations should be sited away from the influence of obstructions such as buildings, trees, small hills, etc. and the influence of non-homogeneous surface conditions (paved or graveled areas, large open water surfaces, etc.) to the greatest extent possible. The extent to which measurements are representative on a spatial scale depends on the uniformity of the surface, topography, and on soil characteristics such as moisture, color, etc. In all cases, obvious micro-environments (tops of ridges, steep slopes, narrow valley bottoms, sheltered hollows, sites significantly influenced by diurnal atmospheric patterns, etc.) should be avoided unless the characterization of that micro-environment is the specific purpose of the weather measurements. In such cases, station site documentation (clause 7.2) should explicitly state the purpose of the measurements.

8.1.1 Wind. Recommended anemometer and wind vane exposure calls for separation distances between sensors and obstructions of a minimum of 10 times the height of the obstruction, and preferably greater than 50 times the height of the obstruction. The influence of vegetative crop growth and development through the growing season should be considered. Wind instruments are preferably mounted on top of masts, but if side-mounted on a boom, the boom length should be at least three times the mast or tower width and the boom should be mounted on the prevailing wind direction side of the mast. Instruments must be installed and maintained in a level position.

8.1.2 Air temperature and relative humidity. Generally these sensors will be co-located or integrated into one unit where one of each measurement is made at a weather station. The sensor should be protected from thermal radiation from all sources and directions using a radiation shield. Any additional air temperature sensors at other heights on the weather station should use an identical radiation shield. At a minimum, a naturally ventilated radiation shield that allows free circulation of air around all sides of the sensor should be used. The shield should be reflective (white) to avoid extraneous heat build up. The recommended separation distance between sensors and nearby obstructions is 4 times the height of the obstruction, and at least 30 m from large paved or graveled areas. Temperature/RH sensors installed on towers should be installed on booms, with the boom length equal to at least the width of the tower.

8.1.3 Solar radiation. The site should be free of obstructions above the plane of the radiation sensing element. Care must be taken that no part of the weather station structure or tower casts a shadow across the radiation sensor at any time of day or year. Reflections from nearby objects and artificial sources of radiation should be avoided. The instrument must be installed and maintained in a level position.

8.1.4 Precipitation. Rain gages should be sited on open ground with the top of the opening level and open to the sky. The separation distance between obstructions and the instrument should be at least twice, and preferably four times the height of the obstruction. Some sheltering may be desirable to reduce turbulence around the gage. Windshields can be used to reduce wind speed at the mouth of the gage.

8.1.5 Soil temperature. Soil temperature probes should be installed at the desired depths and under the desired surface conditions with soil water contents maintained at levels equivalent to the soil environment being represented (i.e., irrigated vs. rainfed). In the case of a single soil temperature measurement, it is recommended in Table 1 to install the probe under bare surface soil conditions at a depth of 0.10 m.

8.2 Measurement surface. The station should be installed over uniform, low-cover vegetation such as grass. In arid areas, natural rainfed cover is acceptable, although it may be preferable to establish and maintain a drought tolerant grass species beneath the station. The preferred installation will be over green grass vegetation having adequate soil water to support reference evapotranspiration rates. The underlying measurement surface should be homogeneous with respect to surface roughness, surface temperature, and surface moisture, particularly in the prevailing wind direction.

8.3 Fetch. The extent of the homogeneous area surrounding a station (or fetch) is traditionally recommended to be 100 times the height of the measurement above ground surface. This "ensures" that sensors (wind, temperature, and relative humidity) are placed within the fully adjusted layer of a newly developing internal boundary layer caused by any surface nonhomogeneities. The purpose(s) for which the weather station data is intended to be used may relax or tighten the degree to which this requirement is followed. For example, if the intended use of the weather station is for computing reference evapotranspiration, the fetch surrounding the station is recommended to be a minimum of 100 m for each 1 m of instrument height and to consist of a green, well-irrigated crop of uniform height. On the other hand, stations intended for integrated pest management (IPM) should be located in, or among, crops of interest, which might not necessarily be of uniform height or might not be well-irrigated all season e.g., orchards or groves.

LeClerc and Thurtell (1990) showed that the "footprint", or the upwind surface area affecting fluxes measured at downwind heights, changes dramatically with surface roughness and thermal stability. The fetch to height ratio of 100:1 may be much too small when measurements are made over smooth surfaces, or during stable thermal conditions.

8.4 Other considerations. Siting considerations should include the availability of local personnel, or cooperators, who may regularly (weekly) perform a visual inspection of station equipment, possibly carry out basic maintenance tasks, and report any problems to station operators.

8.4.1 Access. The site should be accessible by vehicle on a year-round basis for routine maintenance and calibration activities. The site should be away from roads to minimize problems of dust and vandalism.

8.4.2 Power. Automatic remote weather stations configured with the standard array of measurements given in clause 4.1 may be operated independent of any need for AC power at the site. These stations are equipped with DC power and may include a solar panel for trickle charging a rechargeable battery. Certain instrumentation beyond the standard set of measurements may require AC power at the site.

8.4.3 Telemetry. If telemetry is used for transfer of data from the remote station to a central collection facility station, siting may be constrained. For instance, if telephone telemetry is used, economics of standard telephone line installation may constrain station siting. Telephone telemetry using cellular service may eliminate some station siting constraints, however, connection and usage fees may be expensive.

For radio frequency (RF) telemetry, the proximity of the station to the RF base station, or to an RF repeater station will constrain siting. Line-of-sight between antennae of the weather station and the base station, or between the weather station and repeater station is generally recommended. This constraint becomes a necessity in the UHF band, unless stations are very close. Satellite telemetry generally imparts few siting constraints.

8.4.4 Security. Site security is a secondary, but important, consideration. When considered necessary to protect facilities and/or instrumentation, protective fencing surrounding a weather station site should not exceed 2 m in height, and should be installed to maintain the recommended separation distances for sensors given in clause 8.1.

9 Calibration and maintenance

9.1 General maintenance and calibration guidelines

9.1.1 Personnel. Only properly trained personnel should perform all maintenance and calibration activities.

9.1.2 Frequency. Routine maintenance at weather station sites should be performed on at least a quarterly basis. (See clause 9.3)

9.1.3 Spare parts. A spare parts inventory (data loggers, power supplies (battery packs and solar panels), sensors, telemetry equipment, hardware, etc.) of at least 10–15% of total equipment inventory should be maintained in ready-to-install condition. This decreases lost data and downtime by allowing immediate replacement of parts that cannot be repaired or brought into proper operation through maintenance and calibration. Also, sensors can be rotated through a laboratory-based calibration and maintenance procedure.

9.1.4 Quality control. Crucial to successful collection and retrieval of high quality data from automatic remote weather stations is the routine processing of incoming data through quality assurance and quality control (QA/QC) algorithms and the regular review of data by experienced, qualified, trained personnel. These reviews are useful for checking reasonableness of data, for flagging of unusual values, and for spotting data values showing unusual consistency or fluctuation. These reviews are preferably performed daily and are an extremely important adjunct to routine scheduled maintenance (clause 10).

9.2 Calibration tests

9.2.1 Data logging equipment. Data loggers should be rotated through a laboratory calibration procedure on an annual basis. Data loggers should be replaced and calibrated in the laboratory or by the manufacturer in the event of electrical transients, or other electrical damage to the data logger or to individual channels. I/O channels on programmable data loggers may be tested with a digital multimeter (DMM) and a program designed to test each channel.

9.2.2 Weather station sensors

9.2.2.1 General considerations. Sensor type and on-site environmental conditions will affect calibration schedules. Detailed, systematic maintenance activities and record keeping will provide considerable insight into the rates of deterioration of sensor calibrations. Physical inspections and cleaning specified in clause 9.3 can be considered a minimal level of effort to ensure sensors operate according to their calibration specifications. Sensors should not be field calibrated, but should be rotated on an annual basis from the weather station to the base for laboratory or manufacturer calibration. The preferable approach is for all sensors to be periodically rotated through a laboratory calibration procedure. Laboratory calibration involves the evaluation of current calibration coefficients and/or derivation of new calibration coefficients through the comparison of sensor output with a known standard at several (minimum of three) points across the operating range of the sensor.

Field sensor performance/intercomparison tests may be performed through accuracy tests using a known input or characteristic, or through side by side comparisons with sensors that are calibrated against a known standard (i.e., preferably against an instrument traceable to the National Bureau of Standards). These standard sensors used for side-by-side comparisons should be used sparingly and only for field intercomparison purposes. They should be either replaced periodically with new, calibrated sensors or routinely subjected to calibration against the known standard to maintain their validity. When sensors are tested side by side with calibration sensors, or against a known characteristic, simultaneous readings are taken over a specified period of time. The percent difference between the averages of the two sets of readings should be computed and compared to previously determined criteria of acceptability or rejection specific to each sensor.

$$\%\ \text{difference} = \frac{(\text{station sensor value}) - (\text{standard sensor value})}{(\text{standard sensor value})} \times 100$$

Side by side comparisons assume the standard sensor is of the same type as the weather station sensor to the extent possible.

All sensors should be subjected to calibration tests upon receipt and before field deployment to ensure proper and accurate operation.

Field tests of a new weather station as a unit should be performed immediately after installation to ensure proper operation of the system. Incoming data from the new station should be carefully screened during the first week of operation to ensure proper operation. Once a new station is operating satisfactorily, routine sensor performance tests should occur at least once a year and preferably every six months.

9.2.2.2 Solar radiation. The standard sensor should be placed at the same height and directly adjacent to the station sensor. The % difference between the two sensors should be less than, or equal to 5%. If this is not obtained, clean the station sensor and repeat the test. If the % difference is still greater than 5%, the station sensor should be replaced and subjected to a thorough laboratory calibration over a complete range of sunlight conditions. A completely opaque cover over the sensor may be used to perform a zero check.

9.2.2.3 Air temperature. Place an aspirated psychrometer at the same level as the temperature sensor in the radiation shield with the psychrometer's thermometers shaded and facing north. Compare temperature readings of the weather station sensor with readings from the dry-bulb thermometer of the psychrometer when maximum depression of wet bulb is achieved. Some difference is expected due to differences in shielding of the two temperature sensors and the fact the sensors are of two different designs.

If differences are greater than instrument accuracy specifications and the tests are being conducted under warm, calm conditions, repeat the test with the weather station sensor removed from the radiation shield, but with both sensors shaded. If the difference is still unacceptable replace the weather station temperature sensor.

Lab calibration of temperature sensors may be accomplished using a stable thermal mass of known temperature, having a time constant of more than 1 hour and design such that there are no thermal sources or sinks to create local gradients within the mass. Alternatively, calibrations may be performed against a precision laboratory thermometer in a temperature controlled water bath, or in a temperature controlled environmental chamber.

Resistance temperature devices (RTD) tend to be very stable and generally do not require calibration.

9.2.2.4 Relative humidity. Use a battery-powered aspirated psychrometer or an Assmann psychrometer (with clean wicking on the wet-bulb thermometer, wetted with distilled water, and a calibrated thermometer pair that matches ambient temperature before wetting of the wet-bulb) to obtain several readings of wet- and dry-bulb temperature. Determine relative humidity from these wet-/dry-bulb pairs using a computer or hand-held calculator program with elevation correction for atmospheric pressure or tables that can be corrected for elevation. Ensure wicking on the wet-bulb remains wet throughout the entire test. Record sensor RH values simultaneously with psychrometer readings.

Deviations of greater than 5-10% between the paired readings indicate a calibration or other problem with the weather station RH sensor. Remove the station sensor from the radiation shield and repeat test. If no improvement occurs, clean the sensor as thoroughly as possible (a few sensors allow water immersion, but subsequently require considerable time to "dry-down" to ambient conditions) and repeat test. If the % difference is unacceptable, the sensor should be replaced and subjected to laboratory calibration or the sensing element replaced if it is replaceable.

Lab calibrations of relative humidity sensors may be developed using saturated salt solutions, or against a standard device such as a calibrated dew-point hygrometer in an environmental chamber having temperature/relative humidity control. At least three known humidities should be used to determine a new set of calibration coefficients.

9.2.2.5 Wind speed. Place the standard sensor at the same height as the station sensor and such that there is no interference of the streams of air from the devices. The percent difference between sensor readings should be less than, or equal to, 5%. Test devices are available to drive the anemometer or propeller shaft at known rates of rotation. The station sensor should be tested at three representative rates equivalent to typical wind speeds at the station (e.g., 2, 5, and 10 m s^{-1}). The anemometer or propeller transfer function should produce a quantity (wind speed value) within one increment of resolution (0.1 m s^{-1}) of the known speed.

Starting torque of the wind speed sensor is tested with a torque wrench. If the starting torque is outside the manufacturer's specifications, the result is a higher starting threshold and loss of accuracy in determination of total wind run. Replace bearings and repeat test.

9.2.2.6 Wind direction. Upon installation, ensure station sensor is oriented to provide readings with respect to true north. Templates that resemble the faceplate of a compass can be constructed to fit around the sensor base. Oriented to true north, readings of the wind vane can be taken at each of many azimuth positions after aligning with the template (see clause 9.3.2.5).

9.2.2.7 Precipitation. Tipping bucket type gages with buckets of known tipping depth may be calibrated based on a measurement of the funnel orifice area, from which a volume of water may be computed that produces one tip of the bucket (e.g., 0.25 mm (0.01 in.) per tip).

A more reliable test is to slowly introduce a volume to produce 10 tips, or 100 tips, and to count the number of tips. Using adjusting mechanisms (set screws, etc.) typically found on most tipping bucket rain gages, it is possible to adjust the gage to operate within 1% to 2% difference.

Weighing gages should be calibrated by placing a series of known weights on the gage. The calibration of the gage should cover the total weighing range of the gage and each weight increment should be no greater than 10% of the total weighing range. The weighing gage should be protected from wind during all calibrations.

9.2.2.8 Soil temperature. See clause 9.2.2.3 for lab calibration. In-field reliability of soil temperature sensors may be checked using a laboratory-calibrated insertion type soil temperature probe of appropriate length.

9.3 Maintenance

9.3.1 Site. Perform the following maintenance during each station visit. Security equipment should be maintained in working order through visual inspection and through annual refurbishing as needed. The grounds surrounding the site should be maintained in a condition similar to the surrounding vegetation, but with the additional condition that plant growth should not interfere with operation of the sensors; this should involve weed control, grass mowing, etc. as appropriate. Trash should be picked up and removed as needed. If local personnel are available, the site should be inspected weekly.

9.3.2 Sensors. The following maintenance duties should be performed during each station visit. All leads from the sensors to the data logger should be secured to station structure (if not routed through the interior of the structure) using black UV resistant cable ties. Check the condition of wire/cable ties. Check the condition of all exposed cables and wire leads for signs of UV breakdown, mechanical damage, etc. The length of exposed cable may be minimized by pulling it through flexible plastic conduit.

9.3.2.1 Solar radiation. Carefully clean sensor surface and check instrument mount to ensure the instrument is level.

9.3.2.2 Air temperature. Clean radiation shield(s) housing the sensor. Gently clean sensor of dust, cobwebs, etc. If sensor is housed within a filter element, remove and gently clean filter.

9.3.2.3 Relative humidity. Clean radiation shield housing the sensor. Gently clean sensor of dust, cobwebs, etc. If sensor is housed within a filter element, remove and gently clean filter.

9.3.2.4 Wind speed. Clean anemometer cups or propeller vanes of dust and cobwebs. Check for dents or cracks. Check instrument level. Check anemometer starting torque for bearing condition. Simple checks such as listening for noise in bearings and/or temporarily shielding the anemometer from wind to visually monitor startup and stop responsiveness are valuable diagnostics in determining bearing fatigue and fouling. In dusty environments replace bearings semi-annually.

9.3.2.5 Wind direction. Clean sensor surfaces of dust, cobwebs, etc. Check instrument level. Verify orientation of vane relative to true north and proceed to check sensor output at a minimum of each of the four coordinate directions (N-0 or 360, E-90, S-180, and W-270). Simple checks such as listening for noise in bearings and temporarily shielding the vane from wind to visually monitor startup and stop responsiveness are valuable diagnostics in determining bearing fatigue and fouling.

Significant deviations between sensor output and known compass direction may occur when winds are predominantly from a narrow sector of the compass, this indicates the potentiometer is worn in that area and should be replaced, even though the readings from other directions may be acceptable.

9.3.2.6 Precipitation. Clean all components of gage of dust, cobwebs, insects, etc. Install screens over all ports to the interior of the gage to minimize entry of spiders and insects. Check that drainage ports are clean and functional. Check instrument level (funnel orifice opening and instrument base). For tipping buckets, ensure pulse output is received at data logger correctly for each manual tip of the bucket. Verify movement of bucket over entire range of movement. When gage is installed away from the main station structure, leads from the gage to the data logger should be buried below ground surface in a moisture- and rodent-proof conduit to prevent mechanical damage by grounds maintenance equipment and rodent chewing damage. Conduit encasement should extend above ground to the entry point of the leads to the interior of the gage and up the station structure a minimum of 0.4 m. Each end of the conduit should be sealed. If a windscreen is used, check to ensure it is level and no more than 12.5 mm above the level of the orifice, with the orifice centered within the screen.

Weighing type gages should be serviced at least once each year by washing all moving parts of the weighing mechanism with a solvent to remove grease. If the moving parts of the gage are lubricated, a dry graphite lubricant should be used. If freezing temperatures are not expected, lightweight oil with a specific gravity of 0.8 to 0.9 should be placed in the bucket to retard evaporation. If freezing temperatures or snow are expected, an oil-ethyl glycol antifreeze solution should be placed in the bucket to melt snow by chemical action, to prevent freezing of the solution, and to retard evaporation.

9.3.2.7 Soil temperature. When a sensor is installed away from the main station structure, wire leads from the sensor to the data logger should be buried below ground surface in a moisture- and rodent-proof conduit to prevent mechanical damage by grounds maintenance equipment and rodent chewing damage. Conduit encasement should extend a minimum of 0.4 m above ground at the station structure. The bare soil surface specification for this measurement (see Table 1) requires that a soil sterilant be used, or periodic weeding be performed, to keep the surface above the sensor (approximately 1 square meter) free of vegetation. A laboratory-calibrated bimetallic dial-type insertion thermometer of appropriate length(s) may be used to check sensor output.

9.3.3 Data logging and telemetry equipment. Inspect equipment during each station visit. Check all connections, plugs, etc., including wiring panel for sensor inputs, wire/cable connections to data storage device or to data telemetry equipment. Inspect data telemetry equipment as follows:

9.3.3.1 Telephone communications. The external telephone lines are the responsibility of the telephone company providing service to the site, and procedures for contacting the company when data can not be retrieved and when other potential sources of difficulty have been eliminated should be clearly established. Any internal phone lines and switching equipment (if applicable) should be inspected annually and repaired or replaced as necessary. Modems should be replaced annually and whenever data storage equipment is replaced due to damage/failure. These units should then be tested under laboratory conditions and repaired as necessary to bring them up to specifications.

9.3.3.2 RF Telemetry and satellite telemetry. Check antenna/cable (each station visit). The proper orientation of directional antennae should be verified. All cable connections at the antenna must be maintained in waterproof condition. The cable path to the transceiver should be secure. Inspect cable connections at the transceiver.

Transceiver performance should be checked semi-annually. Use a watt meter to check forward and reflected power. Take corrective action as needed to reduce any reflected power to acceptable levels. The transceiver transmit frequency must be maintained within federal agency guidelines. Check for frequency drift on the transmit side and check receive-side sensitivity. Check the power supply to the transceiver and verify it is within operational specifications for the transceiver.

Appurtenant telemetry equipment (repeaters for RF systems, base station receiving equipment, etc.) should be checked and tests performed as outlined above.

9.3.4 Power supply. During each station visit, perform the following inspections and clean and/or repair as needed.

9.3.4.1. Stations on AC power. Check all power connections. Check and verify output of power transformers with a DMM.

9.3.4.2. Stations on DC power. On stations operated with battery power and no solar panel, check for corrosion at all battery terminals and power cable connectors. Check voltage output of battery pack with a DMM. Maintain a comprehensive written record of battery replacement. On stations with battery power and a solar panel, check for corrosion at all terminals and power cable connectors. Check voltage output of battery with a DMM. Check voltage output of solar panel with a DMM (this may require connection of an artificial load to obtain realistic steady readings). Clean the surface of the solar panel. If the battery is a wet cell type, it should be housed in a separate enclosure. Check fluid levels and refill as needed. Clean and maintain the enclosure as needed. Maintain a written record of battery maintenance and replacement schedule.

9.3.4.3 Cables. Secure all power cables, ground wires, etc. to the station structure using black UV resistant wire/cable ties.

9.3.5 Station structure. Instrument support structures (towers, tripods, etc.) and instrument/electronic equipment enclosures should be inspected semi-annually and painted, repaired, and/or replaced as necessary to keep them functioning properly. Check and tighten all clamps, nuts, bolts, etc. Lightning protection in the form of fully grounded, heavy-duty lightning rods should be provided with these support structures. Support structures and the electronic equipment enclosures must be properly grounded to the lightning rods.

Maintain fresh desiccant inside data logger enclosure. Inspect the desiccant at each station visit and replace as needed with a fresh supply. Check the cable and wire ports into the enclosure to ensure they are sealed.

All cables should be secured neatly to convenient support structures using black UV resistant cable ties and protected from accidental damage by lawn mowers, etc., where necessary. Inspection for damaged or deteriorating cables should be carried out yearly, and cables should be replaced as necessary. Similarly, panels and any other electrical connection devices should be inspected annually for proper performance and maintained in a suitable state of repair.

10 Data management

10.1 Data quality assurance/quality control. Weather data collected by automatic agricultural weather stations or networks of stations should be subjected to quality assurance/quality control (QA/QC) programs for validation before dissemination or archival. A quality assurance plan of action should be formulated that contains all of the information specified in clause 7, Documentation, as well as summary documentation indicating compliance with the QA plan and appropriate updating of the recommended documentation on a regular basis.

10.2 Data validation and flagging. Data validation consists of routine review of data by experienced or trained personnel, screening of data to identify possible erroneous values, and random comparisons of data with other available data. Manual data reviews should be conducted on a frequency relative to the frequency with which data are retrieved at the central processing facility, i.e., daily reviews for data retrieved hourly or daily, etc. Data sets should be scanned for obvious incorrect values, missing data, etc.

Automatic data screening is easily performed by passing incoming data through a computer program that will check the data against specified screening criteria such as the allowable ranges for the data, historical maxima or minima, allowable rates of change, etc. Screening criteria may be based on historical data and physically realistic values. Site-specific screening criteria should be developed for each weather station. Data that do not meet screening criteria limits should be flagged for later investigation.

Data from adjacent stations should be randomly compared to assess whether instrumentation operation/calibration are changing over time. This is often done most expeditiously by using graphical techniques. Discrepancies that cannot be explained by geographic differences or regional climate variability should be flagged for further investigation.

Trained personnel should further evaluate any data flagged by the above procedures. Anomalous flagged data may be left as measured and received, but should be re-flagged with a flag indicating questionable values. Flagged data should be saved. Flagged data values that are replaced with back-up data, nearest-neighbor data, or interpolated values should remain flagged, indicating the action taken. All data changes occurring during the data validation process should be fully documented.

10.3 Data format and archival. Data storage formats for intermediate and long term storage (archival) to be used by the personnel operating a weather station, or a network of stations are not specified here due to the variety of commercial and privately developed database systems in use.

Procedures should be implemented to make all data available upon request to all potential users in a minimum of a fully documented, concise ASCII format. This documentation should include station location data (latitude, longitude and elevation); instrument exposure and deployment heights; and descriptions of the variables (order, format, units). Each record of daily data should be date stamped with the year and day of the year. Each record of data collected on a finer time scale (e.g., hourly or 15-minute) should be time stamped with the year, day of the year, and time of day.

Weather station history (site documentation, maintenance and calibration documentation, etc.) should be made available to all users upon request.

A plan for long term storage or archival of all data collected by automatic agricultural weather stations is recommended. The State Climatologist or the nearest Regional Climate Center should be contacted for advice. Archival formats and procedures are not specified here, however, procedures to produce the minimum recommended ASCII format described above should be implemented.

Annex A
(informative)

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Appendix B- ASCE –EWRI weather station memo

To: Managers of Agricultural Weather Networks and Associated Weather Data Systems
From: Technical Committee on Evapotranspiration in Irrigation and Hydrology of the Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE)
Date: 1 April, 2009

Subject: Quality Assessment and Control of Automated Weather Data

This memorandum discusses the following topics:

- The need for high quality weather data for calculating reference evapotranspiration (ET_{ref})
- Encouragement to your network to test the visually based QA/QC processes proposed by ASCE-EWRI (2005) for adoption by your QA/QC system
- Encouragement to your network to provide public access to final sets of QA/QC'd weather data to leverage QA/QC efforts and to promote economic efficiency
- To call your attention to the ASCE-EWRI (2005) standardization for the calculation of reference evapotranspiration

In 2005 the American Society of Civil Engineers – Environmental and Water Resources Institute (ASCE-EWRI) published "*The ASCE Standardized Reference Evapotranspiration Equation*[1]" that describes standardized calculation procedures for determining reference evapotranspiration (ET_{ref}). The basis of the standardized ET_{ref} equation and definition is the ASCE Penman-Monteith (ASCE-PM) method. Standardized calculations were recommended for vapor pressure and net radiation determination and for wind speed adjustment. A major impetus for the ASCE report was to improve consistency and quality of calculated ET_{ref} and to provide guidelines on assessing weather data integrity. Reference ET and associated estimates of crop ET are coming under increasing scrutiny in the American courts during water rights cases. The integrity of weather data that form the basis of ET_{ref} calculations is increasingly required to "pass muster."

[1] *The ASCE Standardized Reference Evapotranspiration Equation*. Allen, R.G., I.A. Walter, R.L. Elliott, T.A. Howell, D. Itenfisu, M.E. Jensen, and R.L. Snyder.(eds), Am. Soc. Civ. Engrs., 216 p. ISBN 078440805X. Available at: http://www.asce.org/bookstore/book.cfm?book=5430

State employees and private consultants routinely invest considerable time and expense in identifying and correcting errors and bias in weather data sets. Too often, each side of a water case applies duplicative efforts to QA/QC the same data sets. These efforts are typically repeated by other users of data, including hydrologists, planners and ground-water modelers, constituting large expenditures of financial resources. Application approaches and quality of final data sets vary widely.

ASCE-EWRI (2005) recommended procedures for visual assessment of solar radiation, humidity and wind speed data (appendices D and E). The procedures are straightforward and are intended to streamline and speed QA/QC processes to insure and produce high quality and representative weather data for use in calculating reference ET[2]. *The ASCE-EWRI Committee on Evapotranspiration in Irrigation and Hydrology (ASCE-EWRI-ET) encourages your network to test these QA/QC processes and to consider them to complement other QA/QC means employed by your automated weather data management system.*

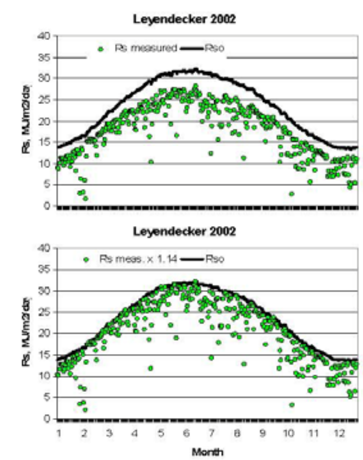
Many automated weather station network systems (AWSN) measure the primary variables affecting ET: solar radiation, air temperature, wind speed and humidity, and therefore provide relatively complete data for calculating reference ET. Because the quality and accuracy of the ET_{ref} calculation is dependent on the quality of the weather data, it is important that the weather data are subjected to a QA/QC process that goes beyond checking of over- or underruns of data extremes relative to established thresholds. It is important that significant over or under measurement or calibration of sensors be rectified. Many AWSN employ QC procedures that compare incoming data against relevant physical extremes (for example, insuring that relative humidity $\leq 100\%$); some use statistical techniques to identify extreme or anomalous values; others compare data among neighboring stations. Some networks flag questionable data while other networks replace questionable data with estimated values. Often, however, these QC procedures are rather broad or coarse, so that products of the QC procedures do not necessarily exhibit data having low measurement bias. This is a primary concern of the *ASCE-EWRI-ET* Committee.

Our sister professional society, the *ASABE*, recently adopted Engineering Practice 505: "*Measurement and Reporting Practices for Automatic Agricultural Weather Stations*" (ASAE, 2004). This standard provides specifications for sensor accuracy, resolution, placement and monitoring, as well as intervals and procedures for sensor maintenance and calibration. The *ASCE-EWRI-ET* Committee supports EP 505 and encourages its use in designing, establishing, locating, and operating AWS networks. The visual data screening and calibration procedures of ASCE (2005) complement EP 505 by providing operational processes for identifying and correcting biased weather data. These procedures are described in Appendix D of ASCE (2005) and are briefly noted in the following paragraphs.

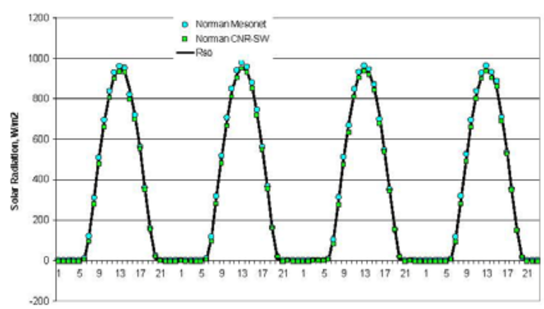
Visual screening of weather data is supported and recommended by *ASCE-EWRI-ET* because it can readily involve the human brain's processing and determination of 'reasonableness' of data in the context of impacts of environmental factors and with implicit comparison to physically known ranges and constraints. In addition, plotted data are conducive to rapid scanning and input by the human.

[2] An early journal paper summarizing the primary processes in the ASCE-EWRI (2005) visual QA/QC procedure is Allen, R.G. 1996. Assessing Integrity of Weather Data for use in Reference Evapotranspiration Estimation. *J. Irrigation and Drainage Engrg.*, ASCE. Vol 122 (2):97-106. A recent summary of the ASCE-EWRI method, including current calibration coefficients for clear sky solar radiation is Allen, R.G. 2008. Quality Assessment of Weather Data and Micrometeological Flux - Impacts on Evapotranspiration Calculation. *J. Agricult. Meteorology* 64(4):191-204.

Solar radiation data, R_s, can be visually screened by plotting measurements against estimates of R_s for clear sky conditions (R_{so}) for hourly or daily timesteps. R_{so} can be readily estimated from Appendix D of ASCE-EWRI (2005) using calculation procedures that include the influence of sun angle, atmospheric thickness (represented by atmospheric pressure), and water content of the atmosphere (estimated from near surface humidity data). When evaluating daily data sets, measured R_s and computed R_{so} can be plotted against the day of the year for one month or one year at a time. Hourly R_s and computed R_{so} data can be plotted against time of day for rapid scanning and assessment of R_s.[3]



A rapid visual review of the R_s -- R_{so} plots provides indication of whether measured R_s "bumps" up against the clear sky envelope of R_{so} on what appear to be cloud-free days for daily data or during cloud-free hours for hourly data. R_s will fall below the R_{so} curve on cloudy or hazy days. If these "upper" values of measured R_s lie routinely above or below the computed R_{so} curve by more than 3 to 5%, then the operator is encouraged to scrutinize the data more closely, to consider impacts of maintenance and calibration of the R_s sensor and datalogging system on the R_s data. Improper calibration, incorrect coefficient, leveling errors, the presence of contaminants on the sensor (e.g., dust, salt, or bird droppings), and electrical problems can cause R_s to deviate from R_{so} on clear days.



Values of R_s that are consistently above or below R_{so} on clear days can often be adjusted by dividing R_s by the average value of R_s/R_{so} for clear periods. Often, a consistent multiplier can be applied over extended periods when the cause of low or high R_s readings stems from miscalibration of the sensor. An example of visual screening of daily R_s data over one year and results of applying a 14% upward correction to the data is shown in the figure above for Leyendecker, NM. The figure to the right shows hourly solar radiation from two collocated sensors at a Norman, OK Mesonet plotted vs. the R_{so} curve on clear days, where one sensor followed the R_{so} curve relatively closely and the second sensor (CNR) averaged a few percent above the curve. Plots of R_s against the R_{so} curve also provides means to assess the accuracy of the datalogger clock, especially with older data sets.

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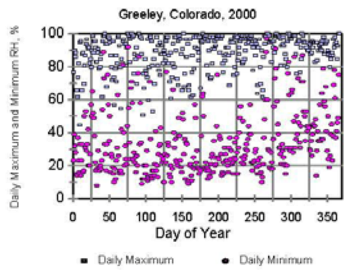
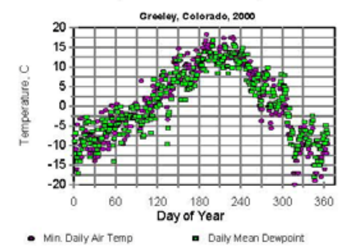
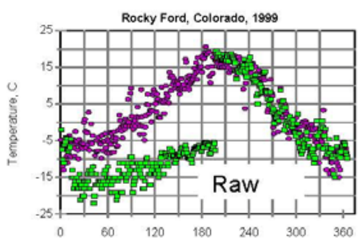
[3] The visual comparisons are often the only available means to assess historical data. For current data collection, a second, dual sensor is encouraged in the case of solar radiation, wind speed, RH and temperature, either mounted permanently or only periodically, to provide redundancy in measurements or to assist in external calibration.

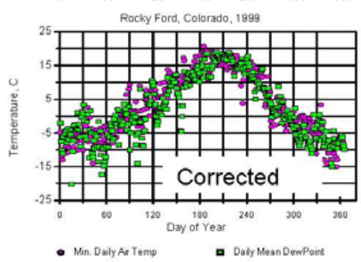
Humidity and air temperature data can be screened to identify questionable or erroneous data. The screening process requires that the user has a sense of reasonable vs unreasonable values. For example, mid-afternoon relative humidity (RH) values chronically lower than 5 to 10% in arid regions and chronically lower than 30% in subhumid regions are uncommon and may indicate problems with the sensor[4]. Similarly, RH values in excess of 100% do not occur in the natural environment and generally indicate that the sensor is out of calibration. The accuracy of most modern-day electronic RH sensors is within +/- 5% RH (ASABE EP505); thus, recorded RH values in excess of 105% suggest the need for correction. Correction of RH data can generally be done using proportional adjustment of all data based on a multiplier and/or offset. The use and magnitude of the multiplier or offset can be based on visual analysis of daily maximum and minimum RH over a period of months. They may also be determined by co-comparison of data among weather stations in the same subregion.

Humidity data can be visually assessed in the form of RH or in the form of a computed dew-point temperature (T_{dew}), or both. T_{dew}, and vapor pressure, e_a, are typically calculated from RH and air temperature, T. Error and bias in RH and T will affect T_{dew} and e_a. Values for daily average and early morning T_{dew} can be compared with daily minimum air temperature (T_{min}). In humid regions, the T_{dew} measurement will typically approach T_{min} most days. Exceptions occur on days that feature a change in air mass (e.g., frontal passage). T_{dew} may approach T_{min} in arid and semiarid environments if nighttime winds are light and measurements are made over a surface exhibiting behavior similar to the reference definition (i.e., sufficient evaporation to cause evaporative cooling). It is not uncommon in arid and semiarid regions to have T_{dew} 2 to 5 °C lower than T_{min} under reference conditions, but well below T_{min} if the measurement site is subject to local dryness. If daily average T_{dew} regularly exceeds T_{min}, then the humidity sensor may be out of calibration. Such data should be examined closely and possibly adjusted prior to use. The example plots of daily maximum and minimum







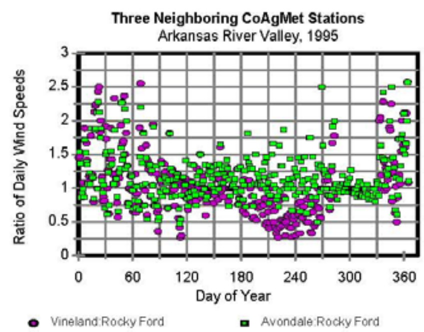


[4] The QA/QC recommendations given in ASCE-EWRI apply primarily to agricultural weather stations and other weather stations whose data are used to calculate reference evapotranspiration that is characteristic of well-watered environments. The ASCE-EWRI ET Committee recognizes that some weather station networks focus on collection of ambient weather data in natural settings. In those situations, air temperature levels may exceed and humidity levels may be lower than those expected in conditioned agricultural settings.

RH and T_{min} and T_{dew} for Greeley, Colorado, above right, show expected ranges, extremes and relationships.

In the case of the humidity data for Rocky Ford, Colorado, above left, a faulty calibration coefficient on RH caused extreme undermeasurement of RH and therefore undercalculation of e_a and T_{dew}. Data were corrected by multiplying the RH measurements over the first half of 1999 by a constant correction factor. The result of the correction on T_{dew} is shown in the bottom figure. In cases where humidity data irreparable, T_{dew} can be estimated from T_{min} using procedures suggested in Appendices D and E of ASCE-EWRI (2005).

Some precautions with scanning RH data are the tendency for some sensors to exhibit a break in calibration slope when RH > 90% (B. Nef, Campbell Sci., pers. commun., 2008).



Assessment of wind speed data generally requires comparisons between wind speed measured at two or more locations. However, a gust factor (ratio of instantaneous maximum to mean daily wind speed can serve as a useful index. Gust factors can increase as contamination increases the friction in bearings. Wind speed at nearby locations are generally related and ratios of wind speed from the two locations is expected to remain relatively constant over time. Plotting ratios over time can identify problems with anemometers or environment. Sudden and consistent changes in ratios often indicate a failed anemometer; gradual change in ratios can indicate growing contamination in bearings or effects of tall vegetation in the immediate vicinity of one of the stations (such as occurred at Vineland, Colorado in the figure above, where the 2 m anemometer was located next to field corn). When possible, the *ASCE-EWRI-ET* Committee recommends that anemometers be located at 3 m above the ground surface to reduce the impacts of surrounding vegetation on reducing wind speed. Wind speed data at the 3 m height can be adjusted to the standard 2 m height for use in standardized ET_{ref} equations using accepted adjustment procedures.

Data flagging and Reporting of Corrected Data. The *ASCE-EWRI-ET* Committee suggests that two sets of weather data (the original (or "raw") and corrected) be housed and made available to users. The nonaltered original data are valuable for assessing the nature and magnitudes of data correction. Some type of "flagging" procedure should be employed to clearly identify data that have been corrected or estimated. In addition, 'meta-data' describing the nature of corrections should be contained within the corrected data archives or be made available as readily assessable reports.

We encourage each network to produce the flagged and corrected weather data sets (as a second data set) to promote economic efficiency, where the data QA/QC and correction is done one time and by a knowledgeable, experienced and trained staff person. This consolidation and centralization of QA/QC will reduce the large number of duplicative corrections by individual data users as is often the case. The *ASCE-EWRI-ET* Committee recognizes that implementation of QA/QC processes may require additional network program funding. However, in the case of State resources, this can constitute an efficient expenditure of public monies, due to the reduction of State resources invested in multiplicative, repetitive data QA/QC by a variety data users (for studies often funded by the State), where the QA/QC is often done by users having insufficient background.

Station Siting. For purposes of calculating ET_{ref}, meteorological data should be measured over and downwind of vegetation that approximates the (well-watered) reference surface. This is important because the standardized ET_{ref} equation was developed for use with meteorological data collected primarily over and downwind of dense, fully transpiring grass or similar vegetation exhibiting behavior similar to the defined reference surface condition. Feedback between and conditioning of the boundary layer exists above an evaporating surface, so that evaporation at the surface impacts temperature and humidity of the air layer above. Studies in southern Idaho by Burman et al. (1975)[5] illustrated how the lower level of the atmosphere changes when going from desert to a patchwork of irrigated and non-irrigated fields. Humidity, temperature and wind speed variables change when entering an irrigated field surrounded by dry or poorly irrigated fields. It is important, when making calculations of ET_{sz}, that weather measurements are accurate and that the weather measurements reflect an environment that conditions the boundary layer as defined by the reference surface.

Ideally, weather stations used to calculate reference ET for agricultural water management and water rights issues should be centered within large, nearly level expanses of uniform vegetation that are supplied with sufficient water through precipitation and/or irrigation to support ET near maximum levels. The preferred vegetation for the site is clipped grass. However, alfalfa or a grass-legume pasture maintained at a height of less than 0.5 m can serve as an effective vegetation. Meteorological measurements made over other short, green, actively transpiring crops will approach reference measurements, provided canopy cover exceeds approximately 70%. A station may be located outside the periphery of a vegetated field provided the station is downwind of the conditioning field during important daytime hours and that vegetation is shorter than about 0.5 m so as to not impact the wind measurement. In an ideal setting, the well-watered vegetation extends at least 100 m in all directions from the weather station. However, it is recognized that frequently such a weather station site is not available, and that often some nonvegetated areas or roadways will be present near the station.

Failure of a weather station site to meet the definition of a reference condition described above does not preclude use of the data for estimation of ET_{ref}. However, data from such a station should be examined carefully, and may, in some cases, require adjustment to humidity or temperature data to make the data more representative of reference conditions (ASCE-EWRI 2005).

The ASCE Standardized Penman-Monteith Reference Evapotranspiration Equation. During the past decade, for convenience and reproducibility, the reference surface has been expressed as a hypothetical surface having specific characteristics (Smith et al., 1991; 1996[6]; ASCE, 1996[7]; FAO-56,

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[5] Burman, R.D., Wright, J.L., and Jensen, M.E. 1975. "Changes in climate and estimated evaporation across a large irrigated area in Idaho." *Trans. ASAE* 18(6):1089-1093.

[6]Smith, M., Allen, R., Monteith, J., Perrier, A., Pereira, L. and Segeren, A. 1991. Report of the expert consultation on procedures for revision of FAO guidelines for crop water requirements. UN-FAO, Rome, Italy, 54 p.
Smith, M., Allen, R.G., and Pereira, L. (1996). "Revised FAO methodology for crop water requiremens." pp. 116-123. In: C.R. Camp, E.J. Sadler, and R.E. Yoder (eds). *Evapotranspiration and Irrigation Scheduling*. Proc., Int'l. Conf., San Antonio, TX, Nov., 1184 pp.

[7]Allen, R.G., Pruitt, W.O., Businger, J.A., Fritschen, L.J., Jensen, M.E., and Quinn, F.H. (1996). Evaporation and Transpiration. Chap. 4, pp. 125-252 In: Wootton et al. (Task Com.), *ASCE Handbook of Hydrology*, 2nd ed" Am. Soc. Civ. Engrs., New York, NY., 784 pp.

1998[8]; ASCE-EWRI, 2005[1]). ASCE-EWRI (2005) defined the standardized reference evapotranspiration as the ET rate from a uniform surface of dense, actively growing vegetation having specified height and surface resistance, not short of soil water, and representing an expanse of at least 100 m of the same or similar vegetation. ASCE-EWRI (2005) established two standardized surfaces to serve the needs of the agricultural and landscape communities and to provide for continuity with past reference ET usage. The ASCE Penman-Monteith (ASCE-PM) equation of ASCE Manual 70[9] was used to represent the standardized surfaces of clipped, cool-season grass (short reference) and full-cover alfalfa (tall reference).

The standardization recommended by ASCE-EWRI (2005) follows commonly used procedures for calculating vapor pressure terms, net radiation, and soil heat flux. The standardization applies the ASCE-PM equation for both reference surfaces using a single equation having fixed constants and standardized computational procedures. The computational procedures were intended to be relatively simple to apply, readily understandable, supported by existing and historical data, technically defensible, and accepted by science and engineering communities. The standardized equation has been investigated over a wide range of locations and climates across the United States. The *ASCE-EWRI-ET* Committee encourages the use of the standardized ET_{ref} equation and procedure in AWS network archives when possible to represent reference ET for the establishment of reproducible and universally transferable ET estimates, climatic description, and derived crop and landscape coefficients.

The ASCE standardized PM method is intended to complement, rather than to replace, other methods currently employed within AWSN for estimating ET_{ref}. The *ASCE-EWRI-ET* Committee recommends application of the standardized reference ET equation and calculation procedures to bring commonality to the calculation of reference ET among AWSN and to provide a standardized basis for determining or transferring crop coefficients for agricultural and landscape use.

The ASCE-EWRI (2005) report[1] includes all necessary calculation equations and information to apply the standardized ASCE Penman-Monteith equation for the grass and alfalfa references. The *ASCE-EWRI-ET* Committee is comprised of 30 professionals involved in ET application and research and represents more than 10 states spanning the US continent. The committee welcomes your comments, feedback and suggestions[10].

This letter is posted as a pdf file that can be downloaded from
www.kimberly.uidaho.edu/water/asceewri/index.html
Pdf copies of the main text of the ASCE-EWRI (2005) report and Appendices D and E describing visual QA/QC of weather data are also available from that site.

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[8] Allen, R.G., Pereira, L.S., Raes, D. and Smith M., (1998). *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*. Irrig. and Drain. Paper No. 56, United Nations Food and Agriculture Organization,. Rome, Italy, 300 pp.

[9] Jensen, M.E., Burman, R.D. and Allen, R.G. (1990). *Evapotranspiration and Irrigation Water Requirements*. ASCE Manuals and Reports on Engineering Practice, No 70, 350 pp.

[10] Current officers of the ASCE-EWRI Technical Committee on Evapotranspiration in Irrigation and Hydrology are: Michael Dukes, Univ. of Florida, Chair; Suat Irmak, Univ. Nebraska, Vice-Chair; Thomas Ley, Colorado Division of Water Resources, Secretary. Mail contact: Dr. Michael Dukes, Agricultural and Biological Engineering Dept.; 107 Frazier Rogers Hall; PO Box 110570; Gainesville, FL 32611; email: mddukes@ufl.edu; tel: (352) 392-1864 x107; fax: (352) 392-4092

Appendix C – Sensor Degradation and Comparison Data

Data were available for 30 model SRSM2 pyranometers (see figure c- 1). These sensors had an average absolute value of percent drift of 14.1 percent. The average period between calibrations was 101.1 months. Of these sensors, only one unit had zero drift. The SRSM2 sensor was not included with the six regions as with the other sensors due to the limited available data. The SRSM2 sensor data were divided into three regions, those being Panama, Northeast U.S. and tropical climates including the states of Hawaii, Florida and California. The sensors that were located in Panama had an average percent drift of 7.18 percent with a maximum of 11.91 percent and a minimum of 2.08 percent. The average period between calibrations was 155.6 months with a maximum of 164.1 months and a minimum of 134.1 months. There were five SRSM2 sensors located in Panama with all sensors exhibiting drift. In the Northeast U.S. the average percent drift was 14.07 percent with a maximum of 34.85 percent and a minimum near zero. The average period between calibrations for this region was 100.3 months with a maximum of 183.1 months and a minimum of 22.0 months. There were 13 model SRSM2 sensors in the Northeast U.S. region, of which only 1 had zero drift. The tropical like climate region had an average percent drift of 18.72 percent with a maximum of 40.86 percent and a minimum of 1.51 percent. The average period between calibrations was 66.5 months with a maximum of 104.1 months and a minimum length of 36 months. In this region there were 7 sensors, all of which indicated drift.

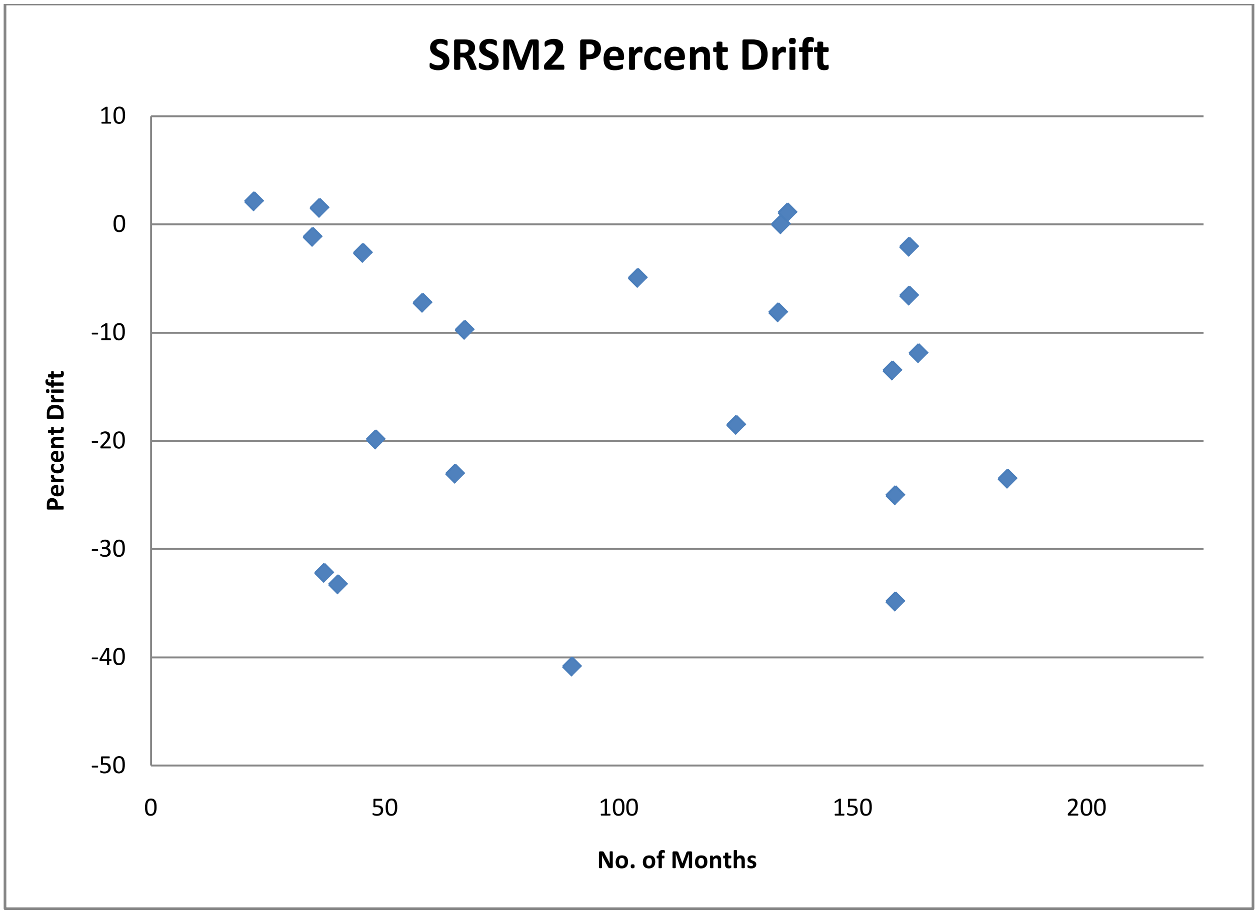


Figure C- 1. Model SRSM2 pyranometer percent output value drift versus time between recalibrations.

There were 305 sensors in the data set for the SRSM1 model (see figure c- 2). The average absolute value of percent drift for these sensors was 5.51. The average period between calibrations was 63.8 months. Of the 305 sensors, 128, or 42 percent, had zero drift. Looking at climate, the SRSM1 in the Northeast region had an average percent drift of 7.52 with a maximum drift of 80.78 and a minimum percent drift of 0. The average period between calibrations was 44.6 months with a maximum of 148 months and a minimum of 0.3 months. There were 98 sensors in the Northeast region, of which 43 had zero drift. The SRSM1 in the Southeast region had an average percent drift of 5.73 with a maximum of 31.07 and a minimum of 0. The average period between calibrations was 69.2 months with a maximum of 235.5 months and a minimum of 11.9 months. There were a total of 84 sensors in the Southeast region, of which 35 had zero drift. In the Upper Midwest, the SRSM1 had an average percent drift of 4.39 with a maximum of 44.21 and a minimum of 0. The average period between calibrations for this region was 67 months with a maximum period of 339.6 months and a minimum of 9.9 months. There were a total of 41 sensors in the Upper Midwest region, of which 13 had zero drift. The SRSM1 in the Lower Midwest had an average percent drift of 11.08 with a maximum of 66.6 and a minimum of 0. The average period between calibrations was 120.21 months with a maximum of 233.23 months and a minimum of 24.2 months. There were 15 sensors in the Lower Midwest region, of which 7 had zero drift. In the Northwest region, the SRSM1 had an average percent drift of 1.34 with a maximum of 11.82 and a minimum of 0. The average period between calibrations was 63 months with a maximum length of 197.9 months and a minimum of 15.7 months. In the Northwest region there were 36 sensors of which 13 had zero drift. The SRSM1 in the Southwest region had an average percent drift of 1.92 with a maximum of 13.88 and a minimum of 0. The average period between calibrations for this region was 82.1 months with a maximum of 369.3 months and a minimum of 7.3 months.

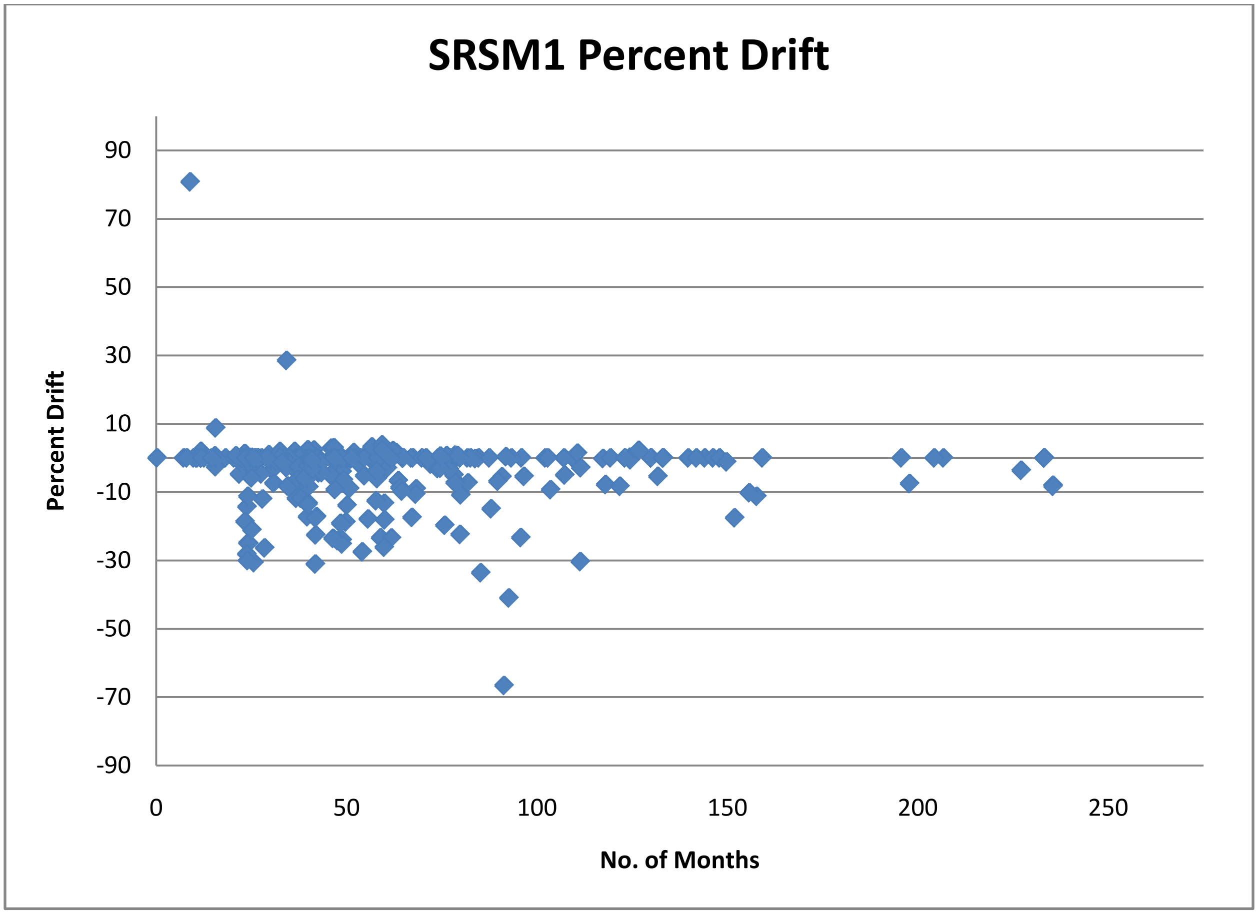


Figure C- 2. Model SRSM1/SRSM25SB pyranometer percent output value drift versus time between recalibrations.

There was data available for 906 SRSM3 sensors (see Figure C- 3). The average absolute value of percent drift was 5.25. The average period between calibrations was 70.47 months. Only 21 percent of the sensors had zero drift. Separating the sensors by regions, the Northeast had an average percent drift of 4.93 with a maximum of 66.18 and a minimum of 0. The average period between calibrations was 58.8 months with a maximum of 207.1 months and a minimum of 0.5 months. There were 99 sensors in the Northeast region with 20 of those having zero drift. In the Southeast region the average percent drift was 7.43 with a maximum value of 88.59 and a minimum value of 0. The average period between calibrations was 66.4 months with a maximum length of 239.8 months and a minimum of 0.3 months. There were a total of 158 SRSM3 sensors in the Southeast region, of which only 42 had zero drift. In the Upper Midwest the average percent drift was 3.41 with a maximum of 19.19 and a minimum of 0. The average period between calibrations was 86.4 months with a maximum of 206.4 months and a minimum length of 0.1 months. There were 90 sensors in the Upper Midwest region with 34 having zero drift. The SRSM3 sensors in the Lower Midwest region had an average percent drift of 5.96 with a maximum of 108.37 and a minimum of 0. The average length of time between calibrations was 60.6 months with a maximum of 168 months and a minimum of 0.5 months. There were 94 sensors in this region, of which 21 had zero drift. Looking at the Northwest region, the average percent drift was 3.87 with a maximum value of 55.85 and a minimum value of 0. The average period between calibrations was 73.9 months with a maximum of 239.3 months and a minimum of 9.7 months. In this region there were 192 sensors with 26 having zero drift. The SRSM3 sensors in the Southwest region had an average percent drift of 4.70 with a maximum of 64.27 and a minimum of 0. The average period between calibrations for these sensors was 69 months with a maximum period of 325.7 months and a minimum period of 0.2 months.

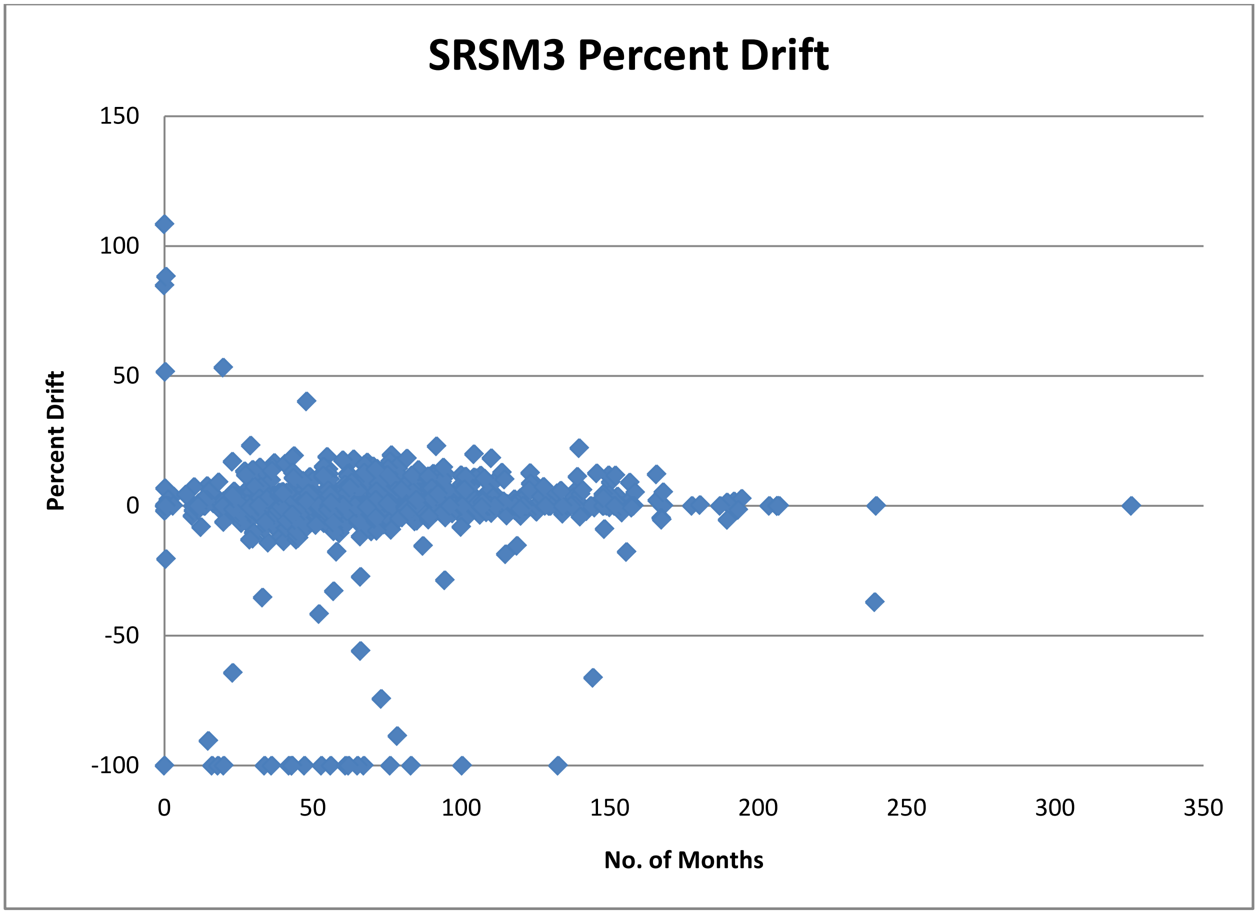


Figure C- 3. Model SRSM3 pyranometer percent output value drift versus time between recalibrations.

There was data available for 253 SRSM4 sensors (see Figure C- 4). The average absolute value of percent drift was 5.53. The average period between calibrations was 54.5 months. Over 99 percent of these sensors had drifted. These sensors were sorted into 5 regions, since no sensors were located in the Upper Midwest region. The Northeast SRSM5 sensors had an average percent drift of 5.12 with a maximum of 13.20 and a minimum of 0.66. The average period between calibrations for this region was 56.1 months with a maximum of 131.6 months and a minimum of 31.4 months. There were 17 sensors in the Northeast region, all of which had drift.

In the Southeast region the percent drift ranged from 0.15 to 80.87 with an average of 7.56. The length of time between calibrations ranged from 31.4 months to 131.6 months with an average of 56.1 months. There were 62 model SRSM4 sensors in this region, all of which drifted. The Lower Midwest region had an average percent drift of 3.14 with a maximum of 14.07 and a minimum of 0. The average period between calibrations for this region was 56.7 months with a maximum of 129.1 months and a minimum of 9.2 months. This region contained 31 sensors, with two of those having zero drift.

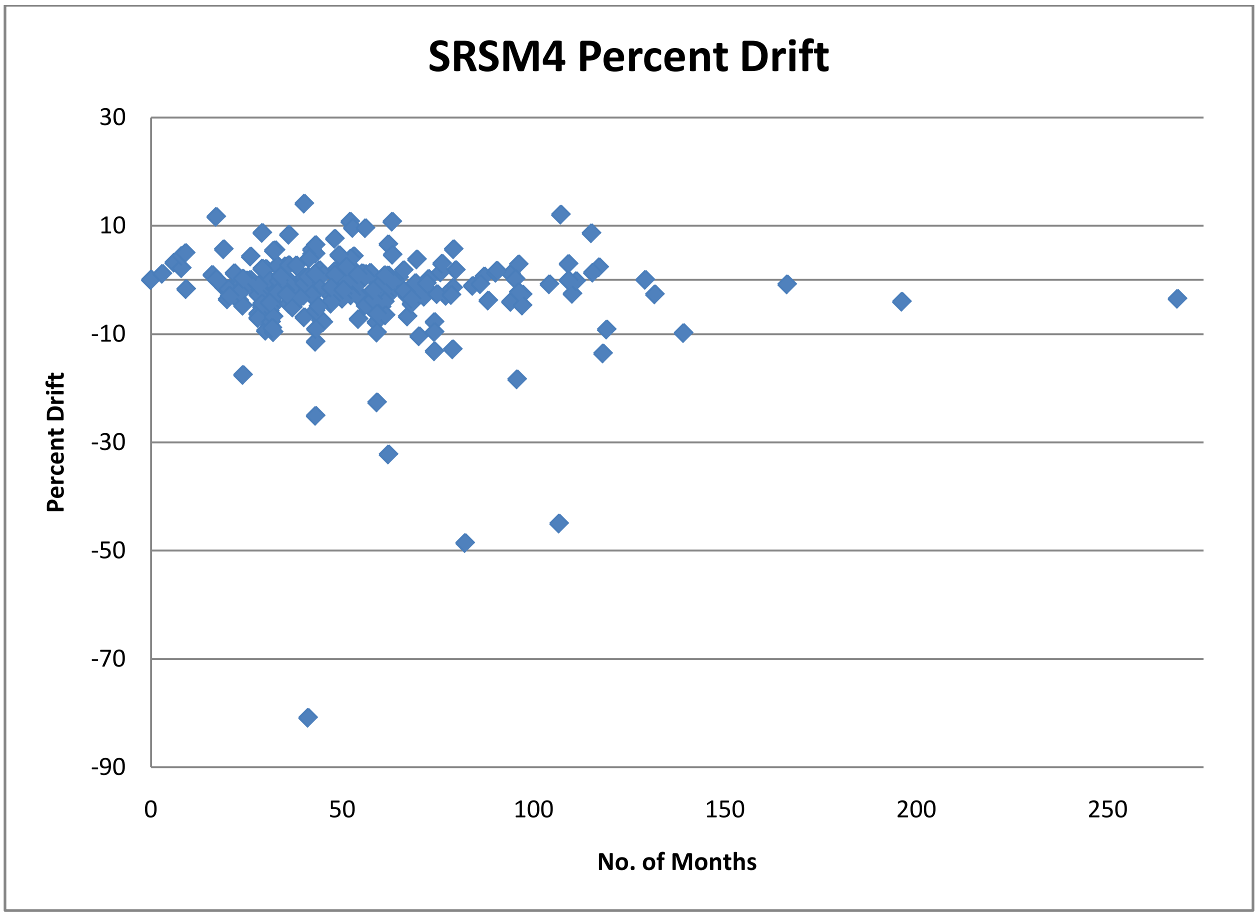


Figure C- 4. Model SRSM4 pyranometer percent output value drift versus time between recalibrations.

In the Northwest, the SRSM4 had an average percent drift of 3.78 with a maximum of 13.59 and a minimum of 0.11. The average period between calibrations was 58.6 months with a maximum of 118.1 months and a minimum of 9 months. The Northwest had 33 sensors, all having drifted. The Southwest region sensors ranged in percent drift from 0.12 to 93.23 with an average drift of 5.63 percent. The period between calibrations ranged from 3 months to 196.2 months with an average period of 54.6 months. This region contained 87 SRSM4 sensors, which all indicated drift.

After separating the data by region, the dataset was edited to look at only sensors that had been recalibrated within 24 months (see Figure C- 5 thru Figure C- 8) to try to identify any correlation that may exist between time and drift. The data showed that drift was virtually independent for the shorter time period as well as for climate. There were data for sensors that had been recalibrated within one month and had indicated significant drift (0.5 months recalibration time with 88% drift) and sensors that had been used for 300 months between calibrations with zero drift. During the graphical analysis, the scales were altered to check for trends within smaller percent ranges with no discernable trend result.

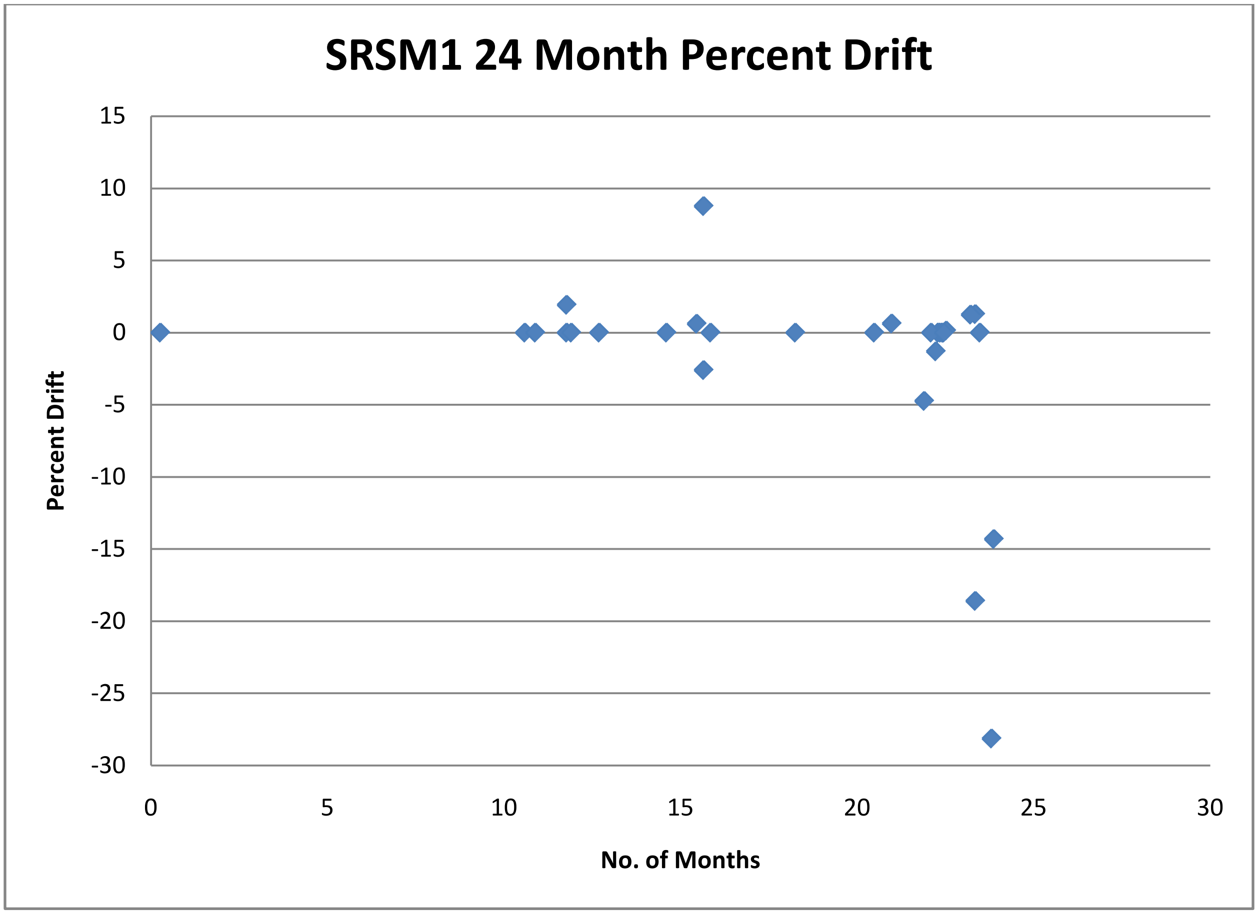


Figure C- 5. Model SRSM1 pyranometer percent output value drift versus time between recalibrations within 24 months.

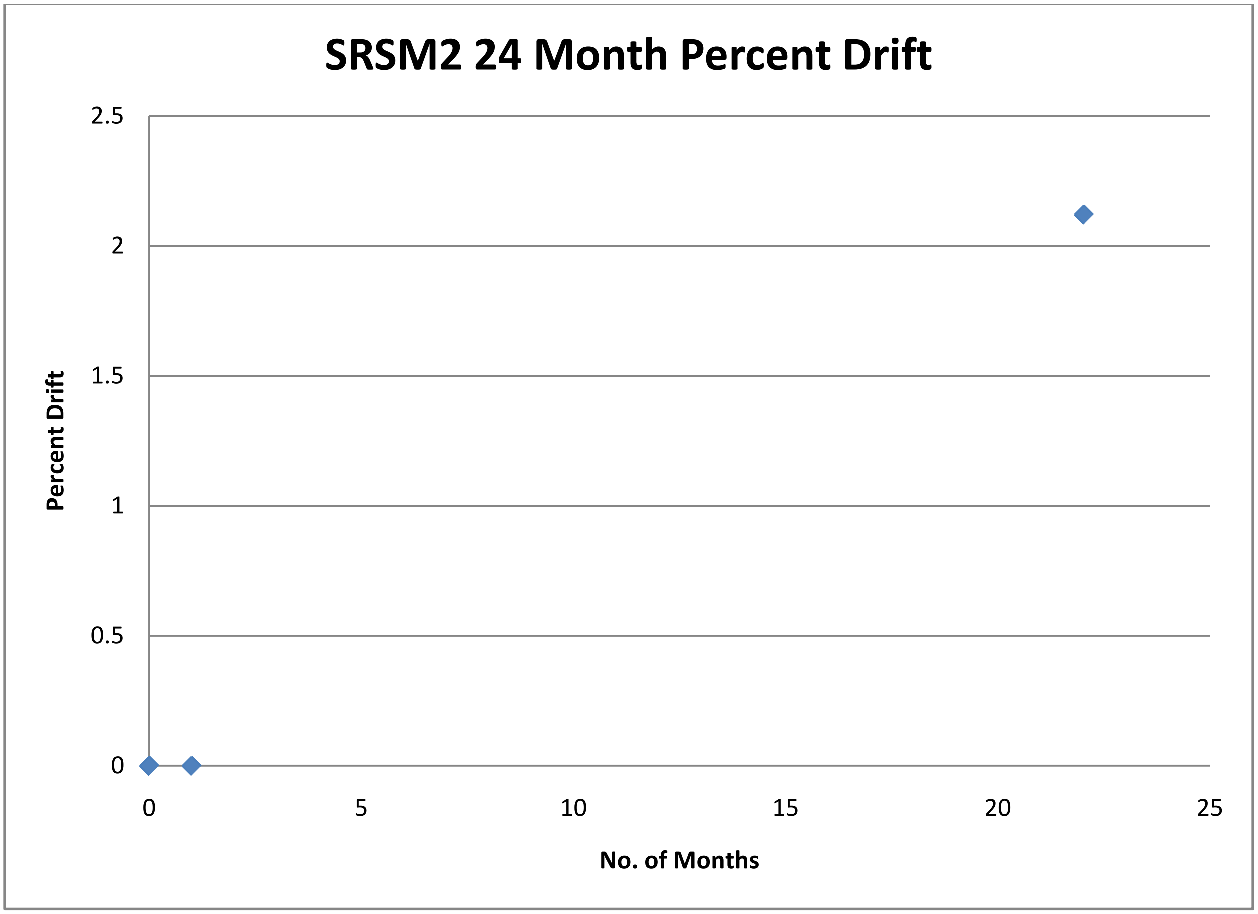


Figure C- 6. Model SRSM1 pyranometer percent output value drift versus time between recalibrations within 24 months.

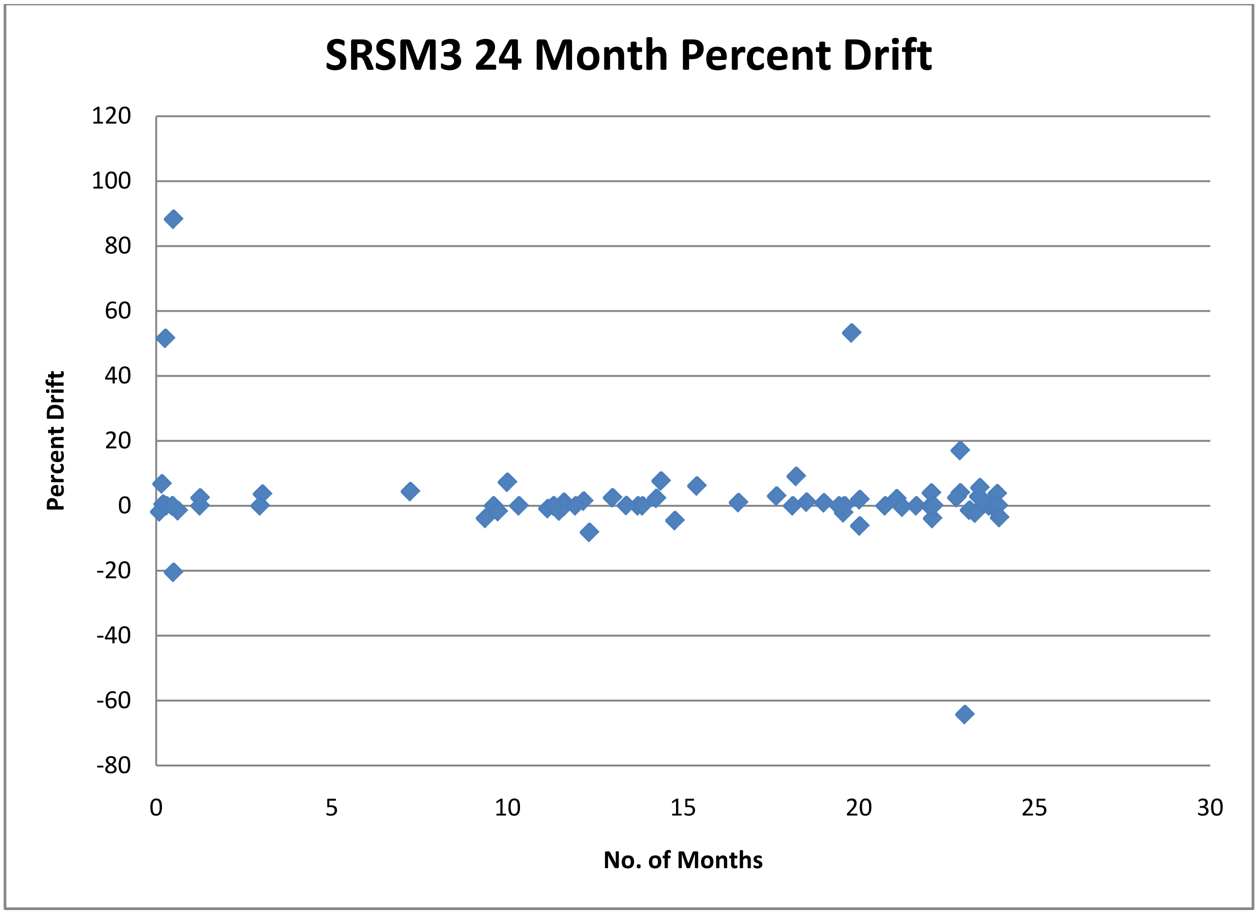


Figure C- 7. Model SRSM3 pyranometer percent output value drift versus time between recalibrations within 24 months.

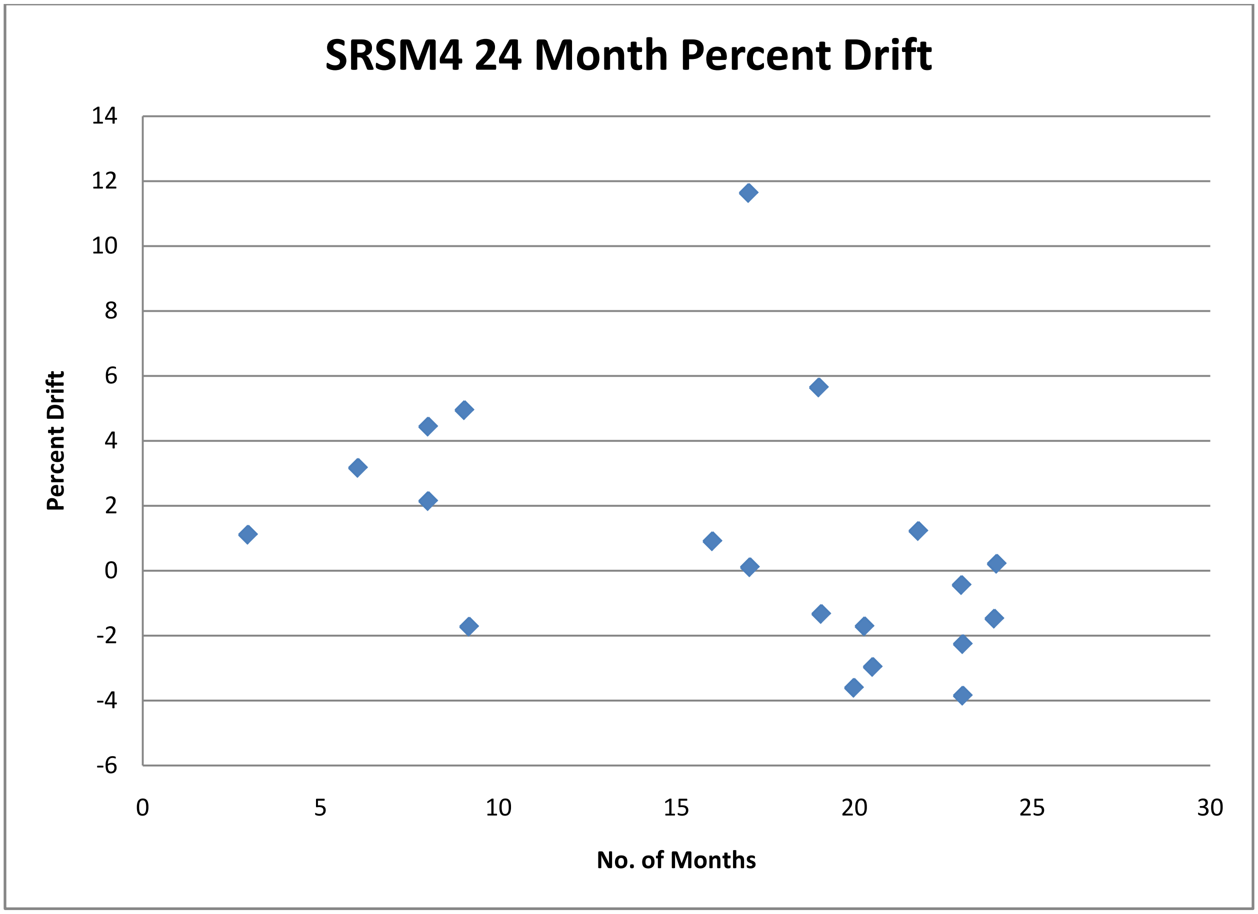


Figure C- 8. Model SRSM4 pyranometer percent output value drift versus time between recalibrations within 24 months.

SRSM1:

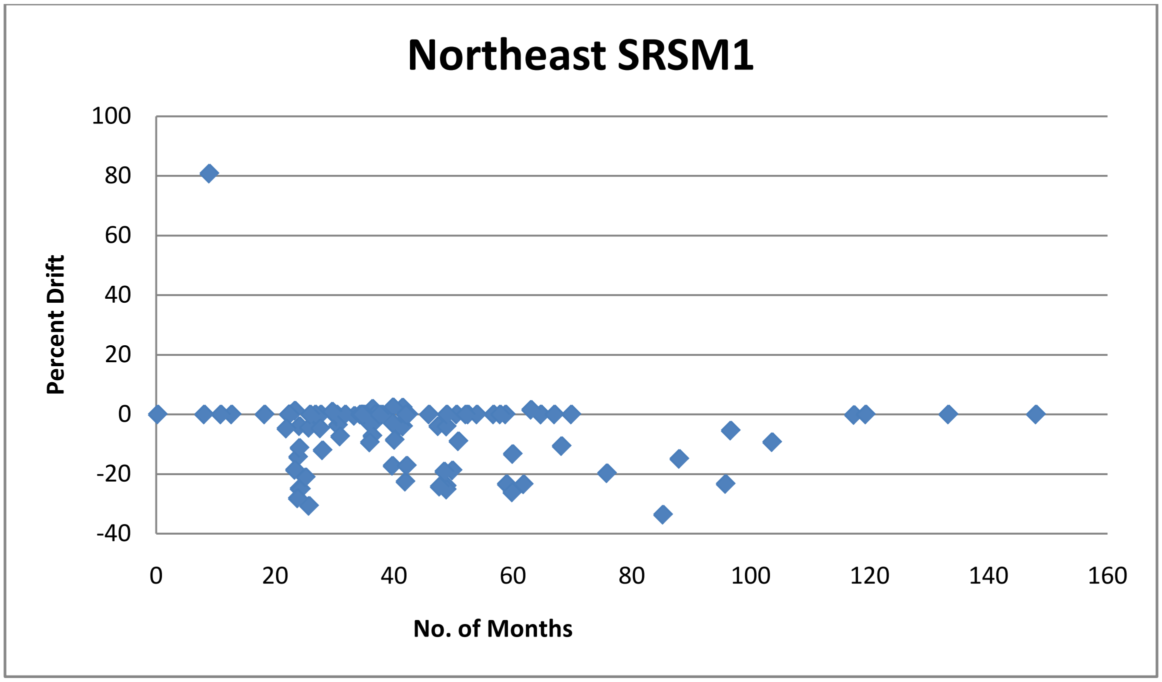


Figure C-9. Plot of Northeast Region SRSM1 percent drift.

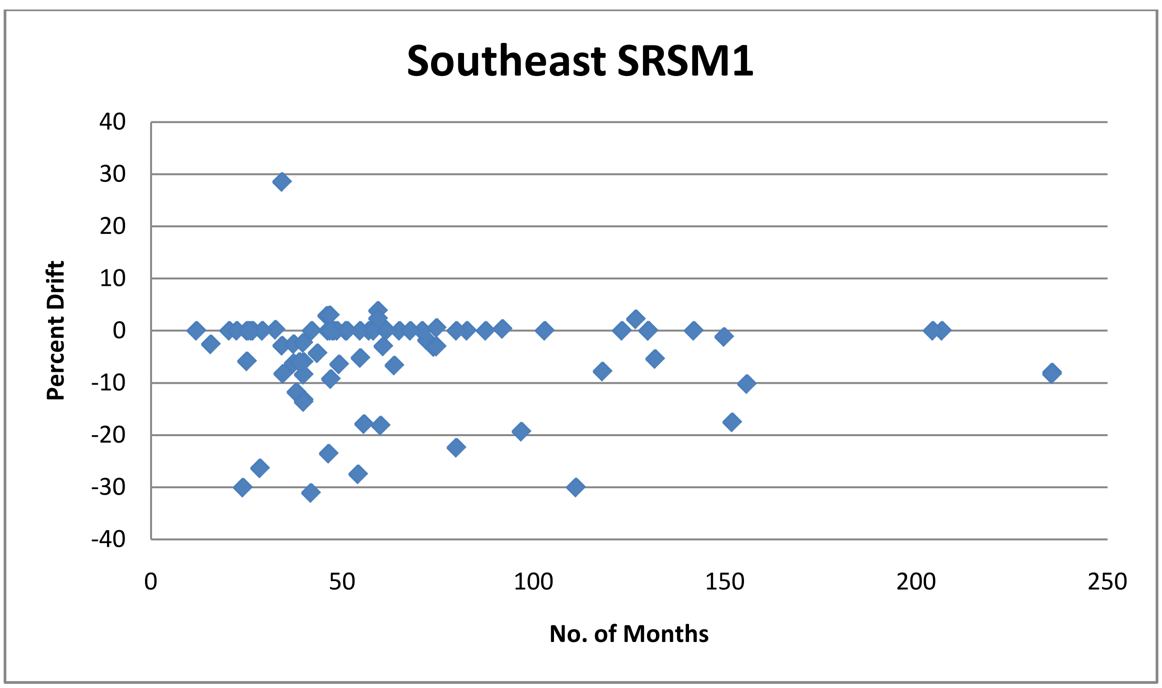


Figure C-10. Plot of Southeast Region SRSM1 percent drift.

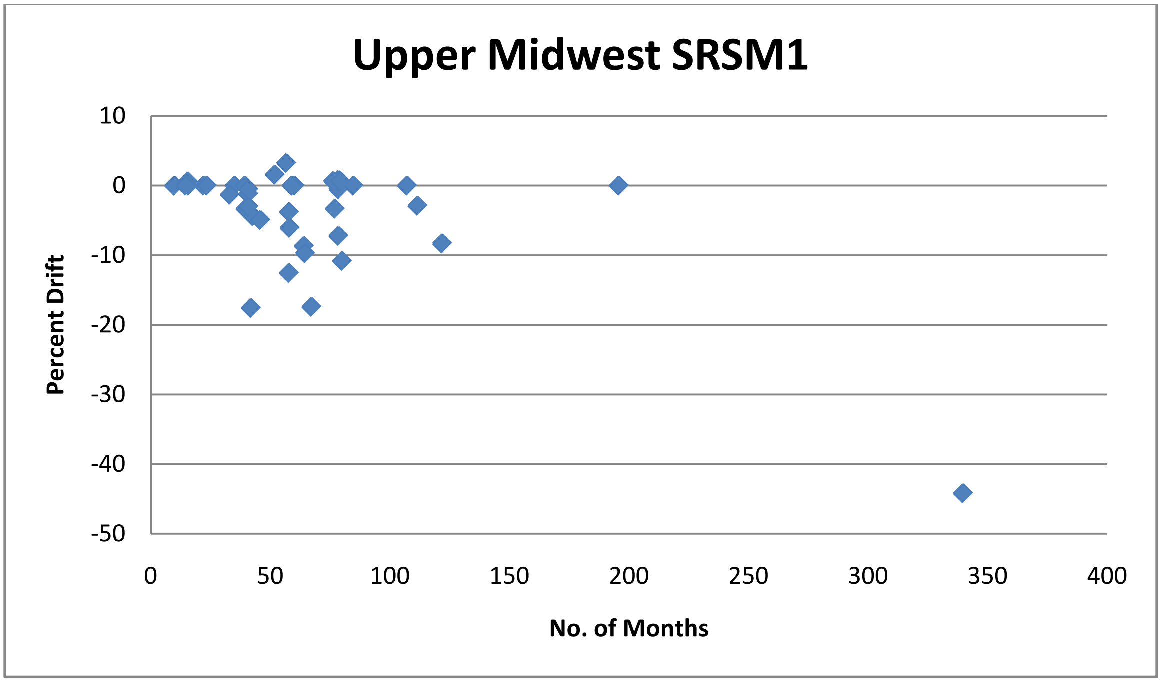


Figure C-11. Plot of Upper Midwest Region SRSM1 percent drift.

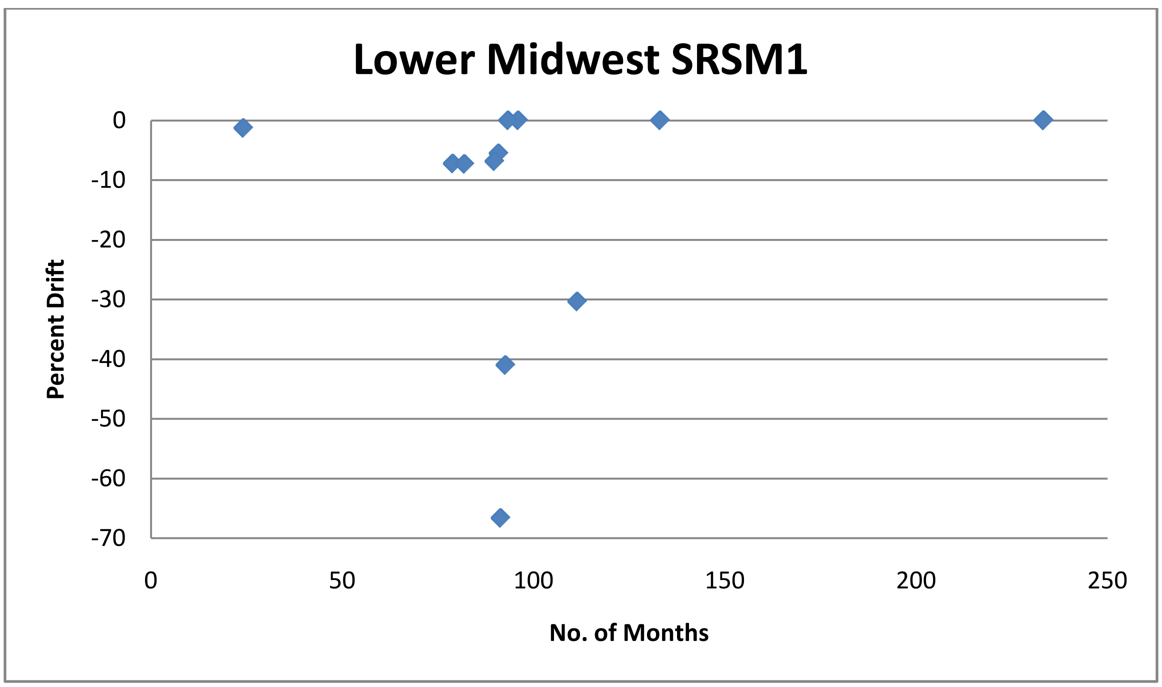


Figure C-12. Plot of Lower Midwest Region SRSM1 percent drift.

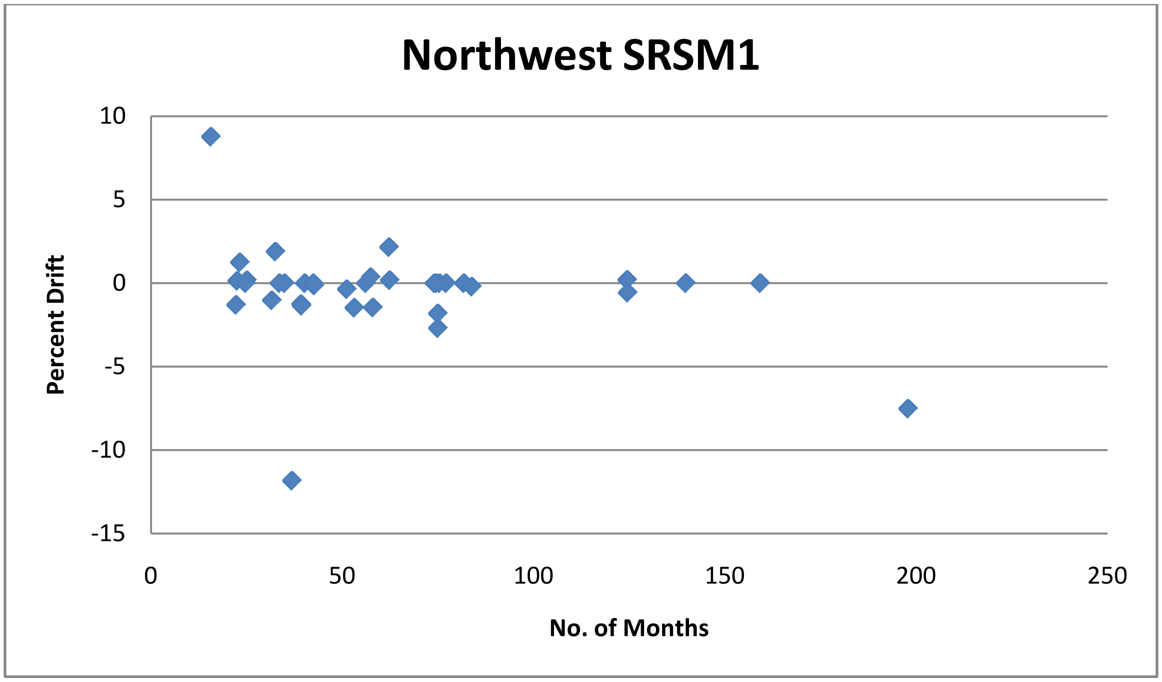


Figure C-13. Plot of Northwest Region SRSM1 percent drift.

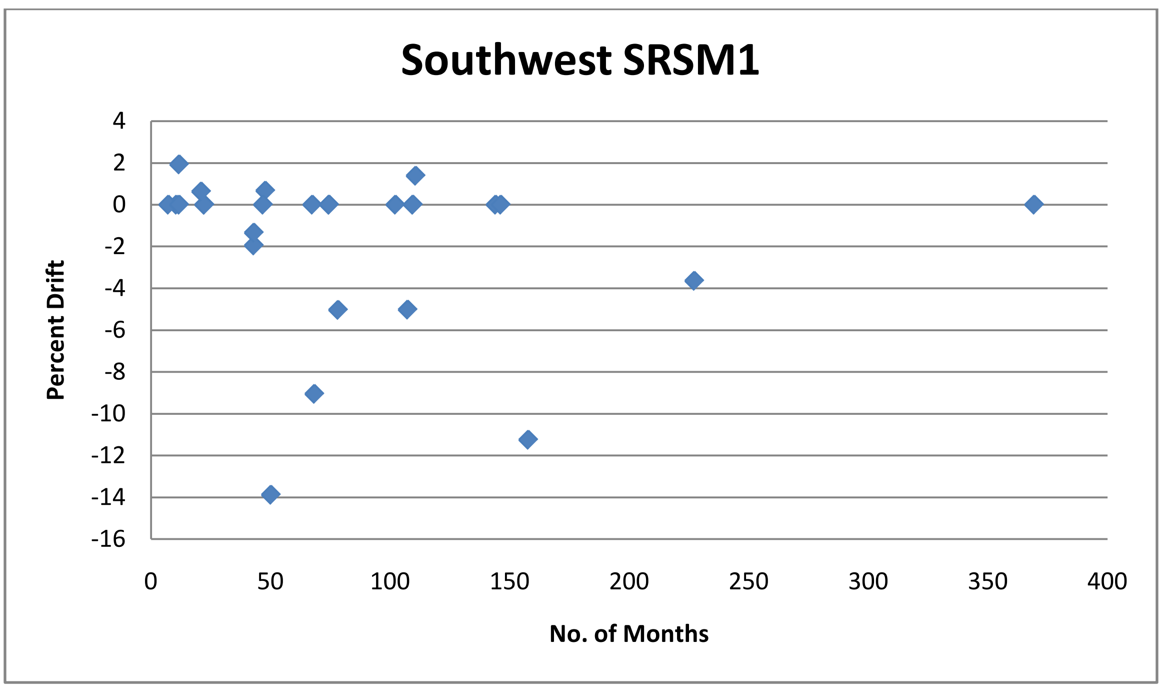


Figure C-14. Plot of Southwest Region SRSM1 percent drift.

SRSM2:

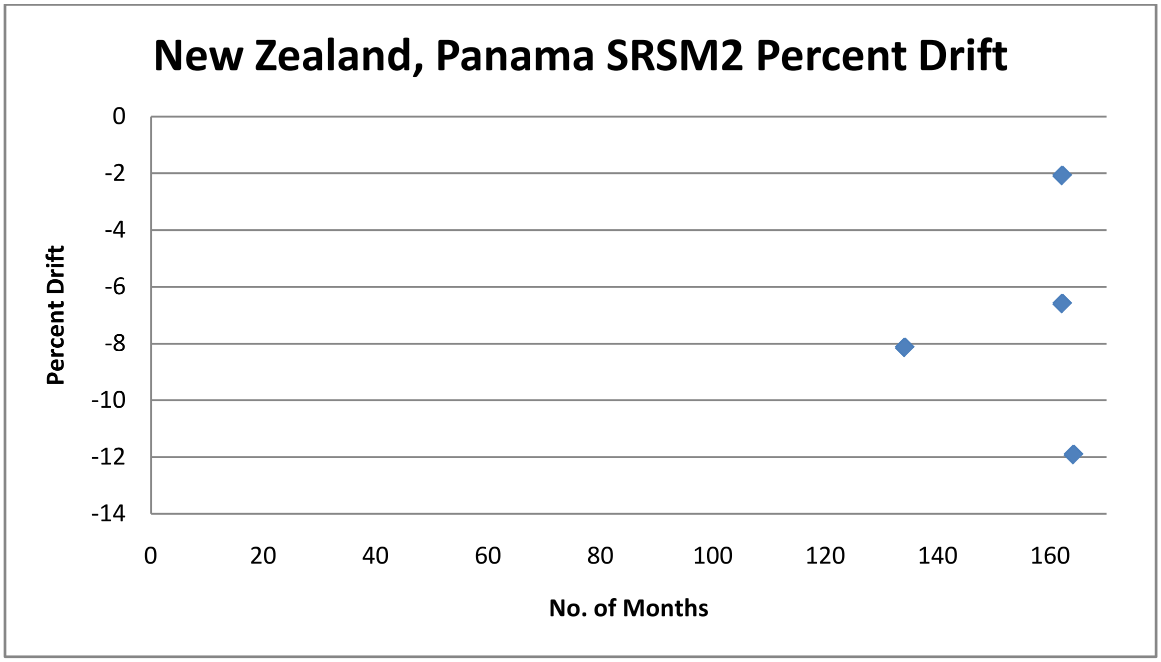


Figure C-15. Plot of New Zealand and Panama SRSM2 percent drift.

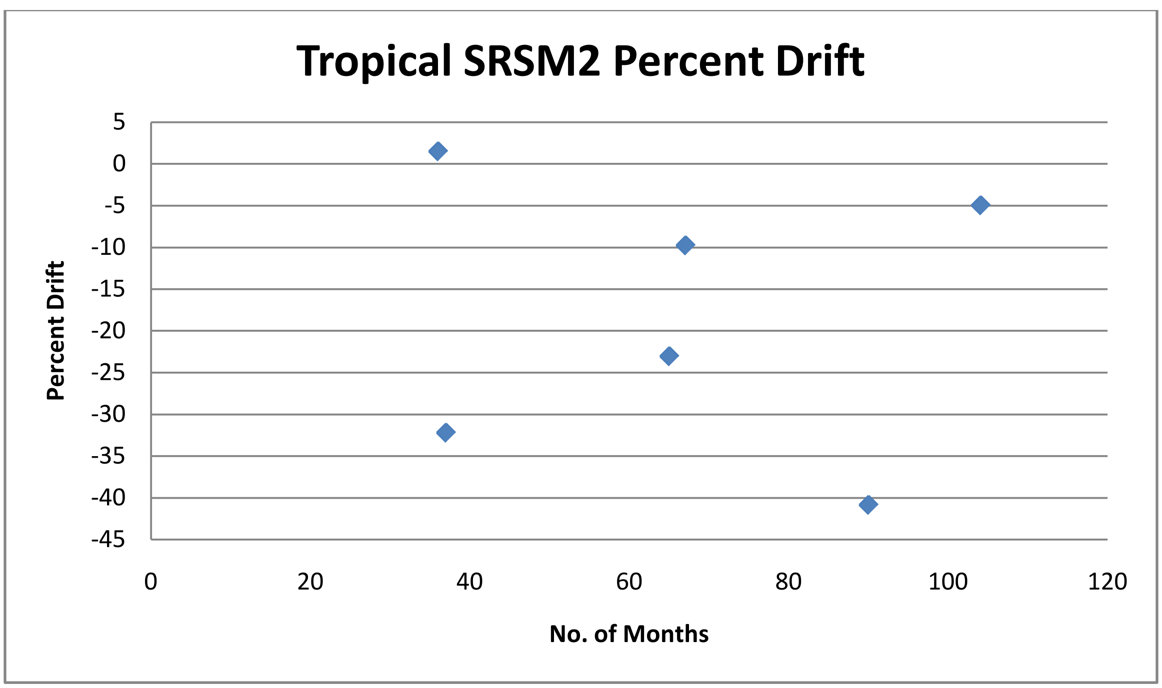


Figure C-16. Plot of Tropical Region SRSM2 percent drift.

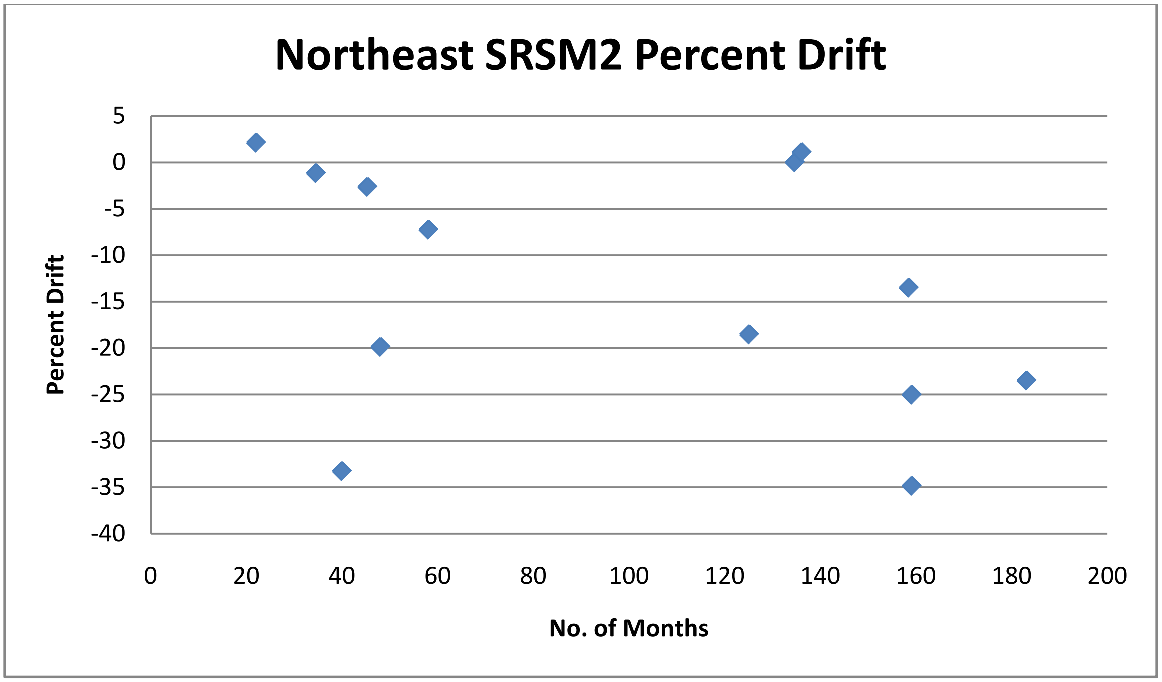


Figure C-17. Plot of Northeast Region SRSM2 percent drift.

SRSM3:

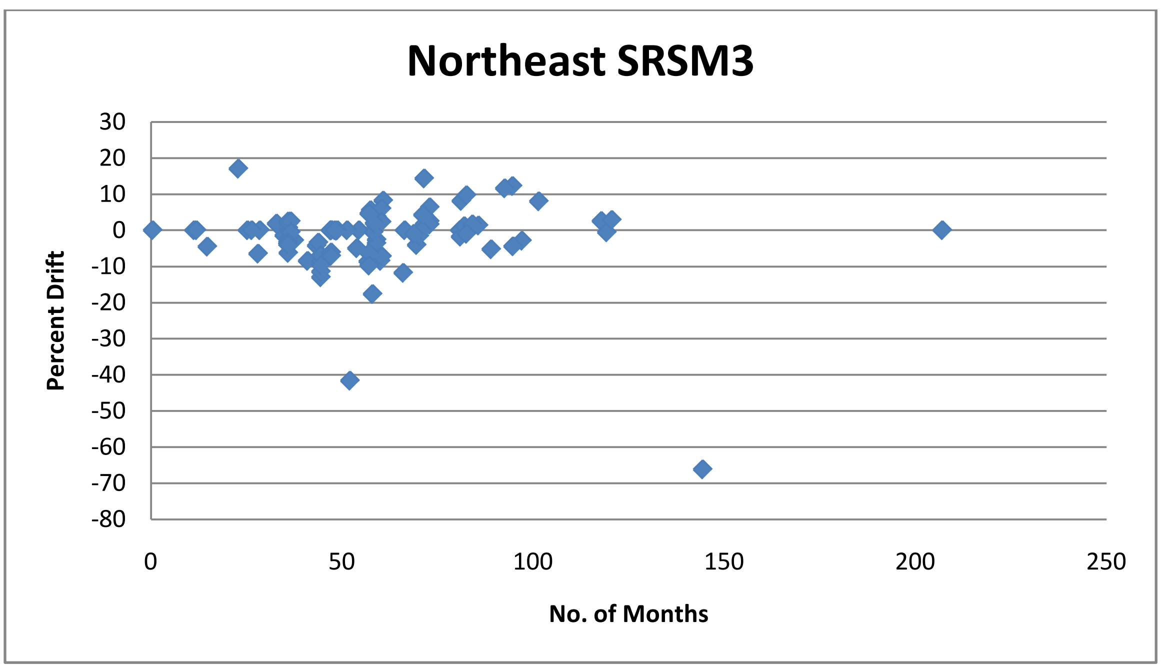


Figure C-18. Plot of Northeast Region SRSM3 percent drift.

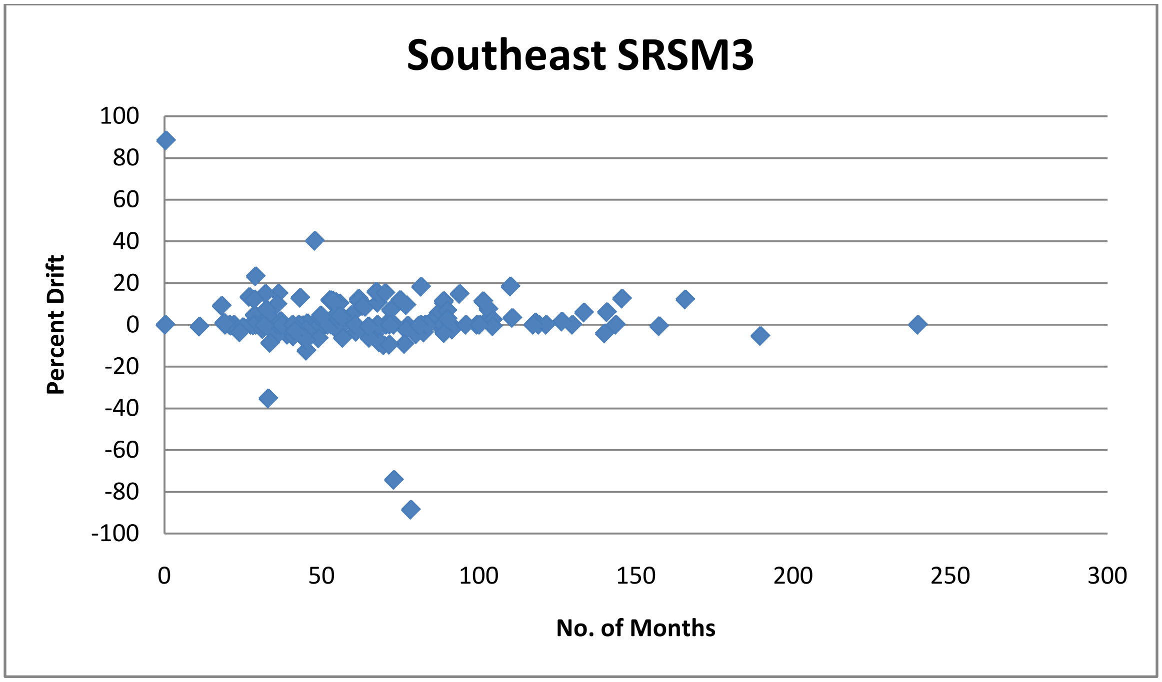


Figure C-19. Plot of Southeast Region SRSM3 percent drift.

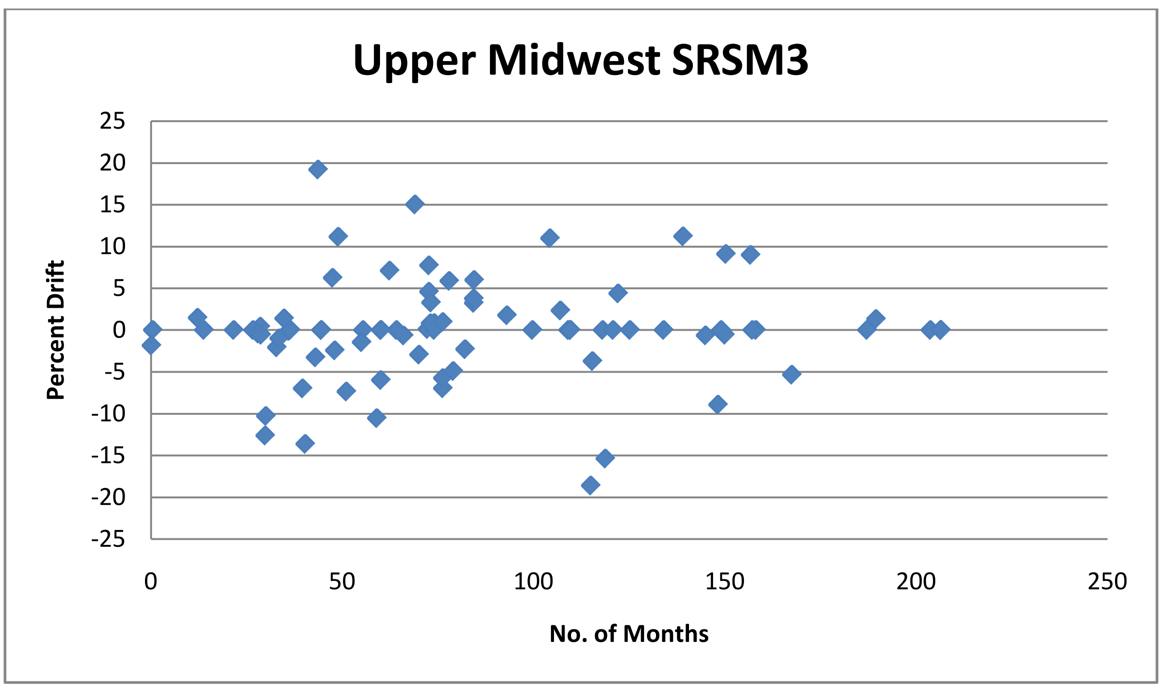


Figure C-20. Plot of Upper Midwest Region SRSM3 percent drift.

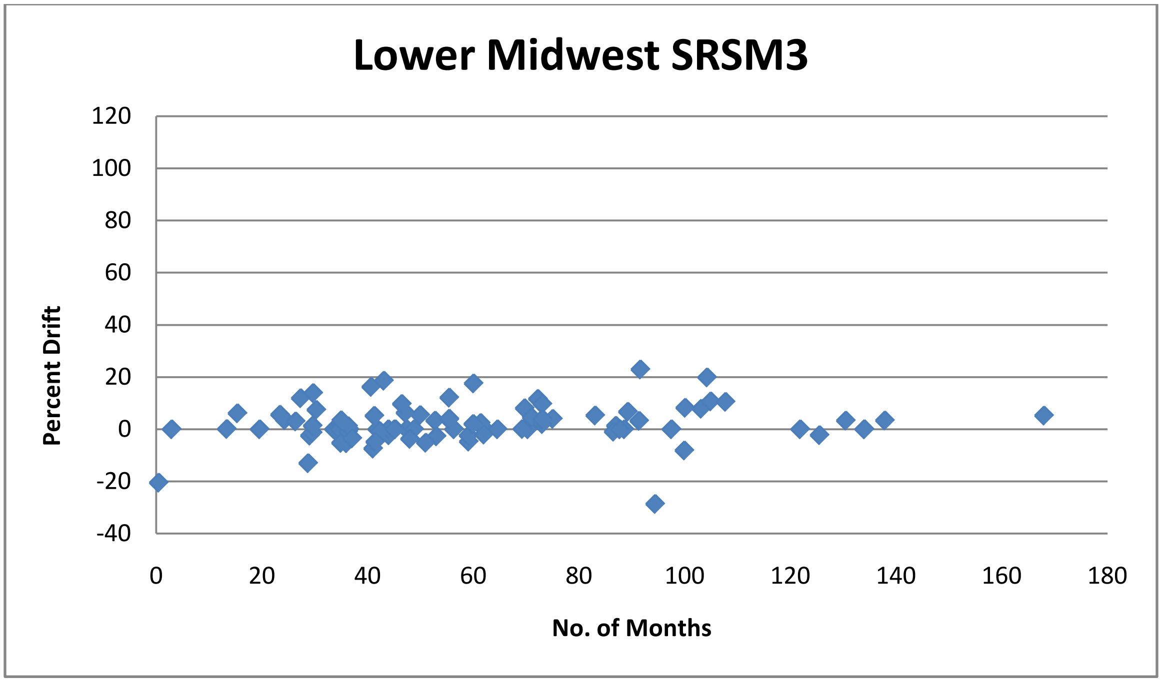


Figure C-21. Plot of Lower Midwest Region SRSM3 percent drift.

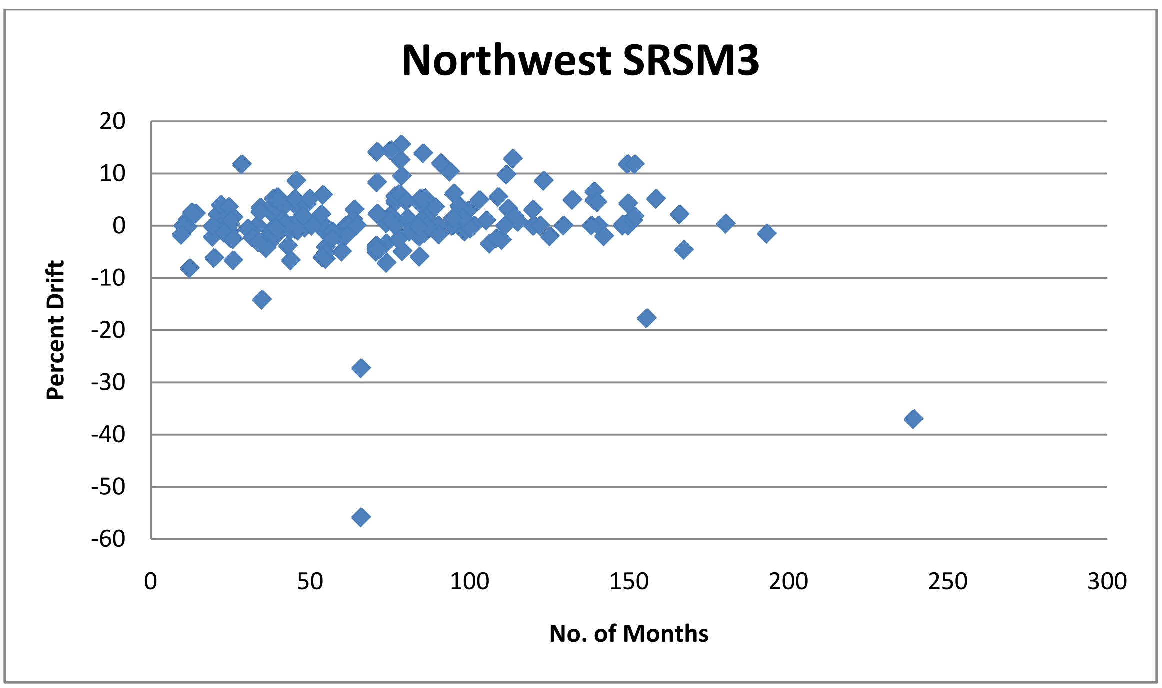


Figure C-22. Plot of Northwest Region SRSM3 percent drift.

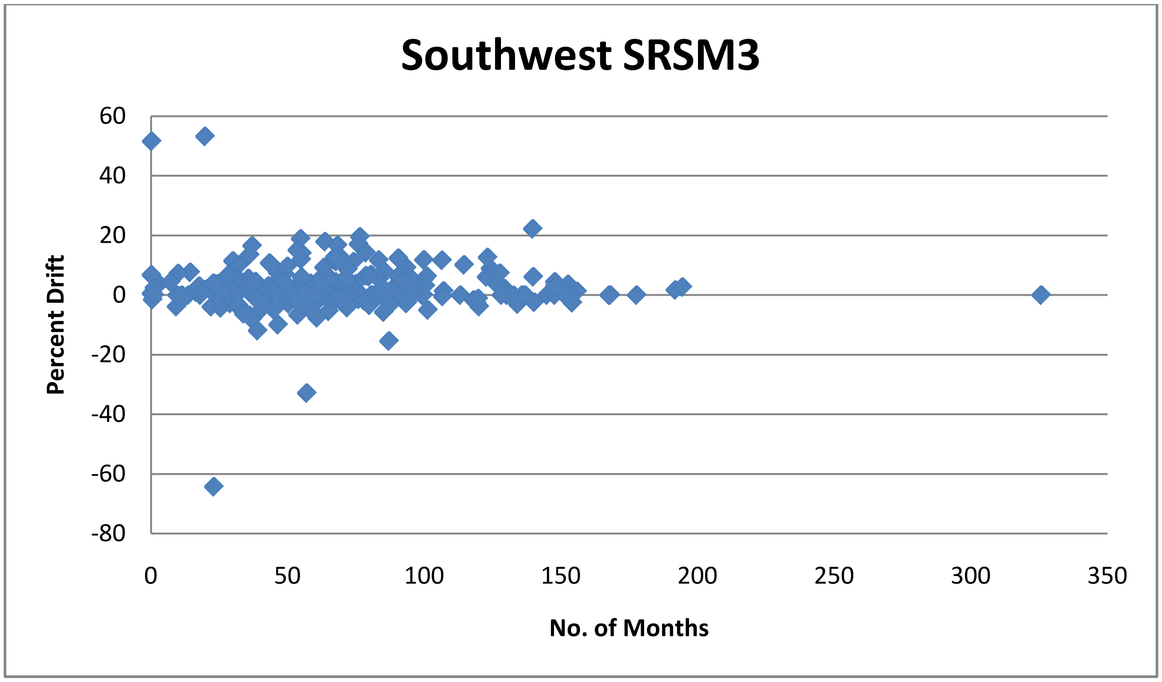


Figure C-23. Plot of Southwest Region SRSM3 percent drift.

SRSM4:

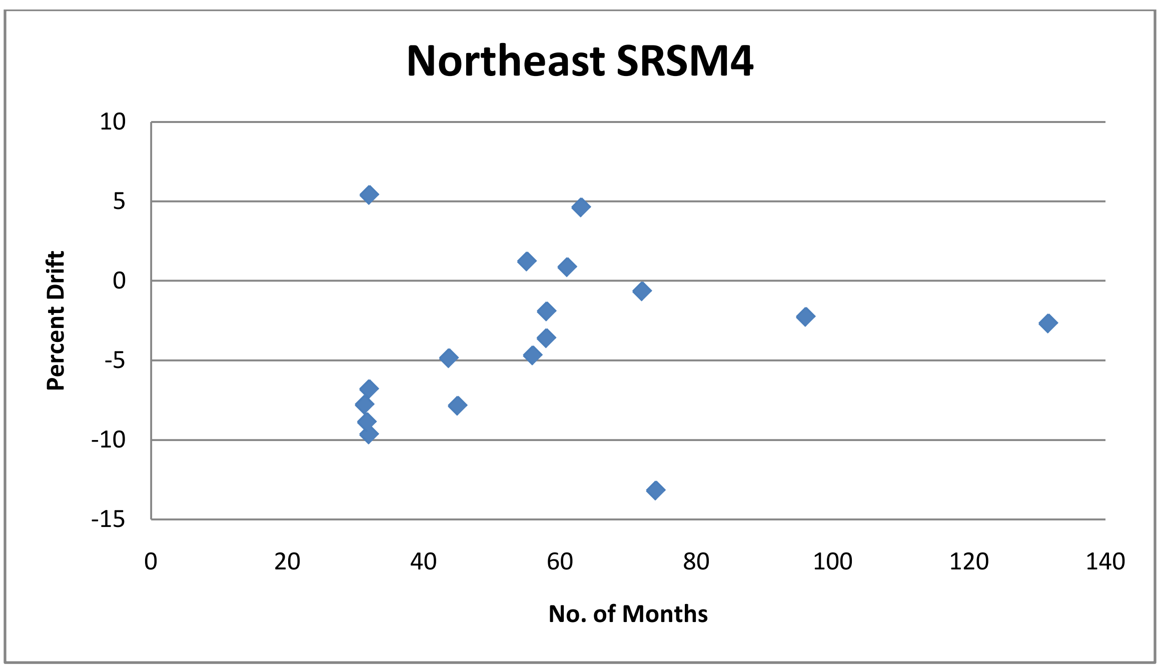


Figure C-24. Plot of Northeast Region SRSM4 percent drift.

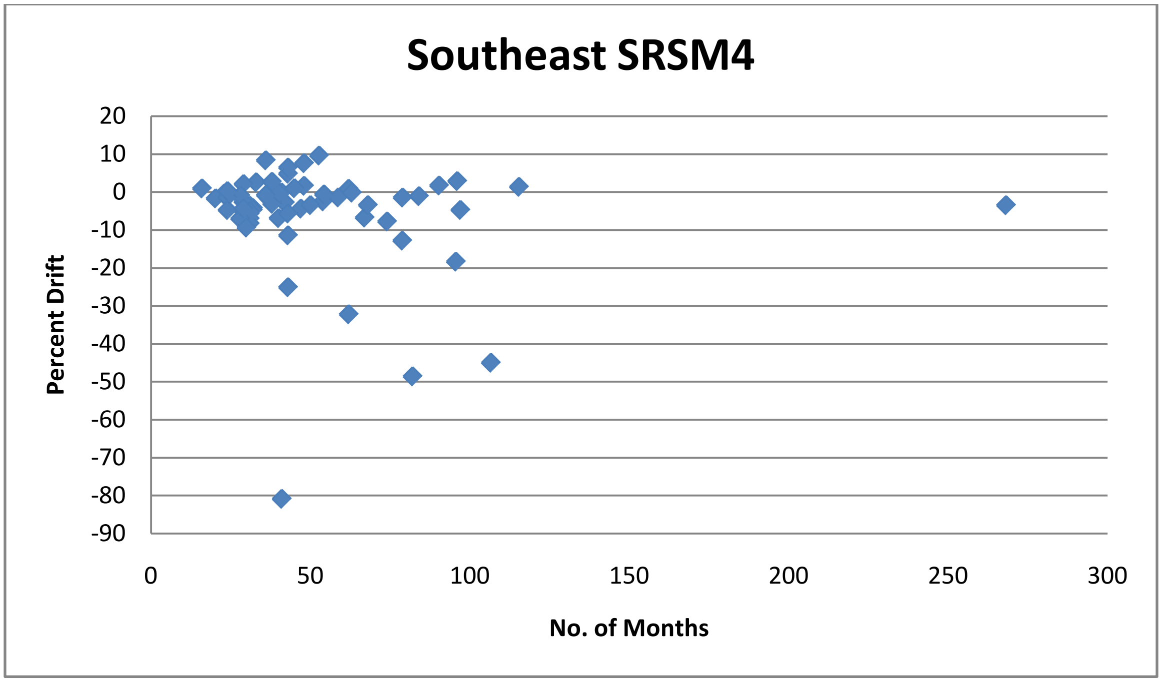


Figure C-25. Plot of southeast Region SRSM4 percent drift.

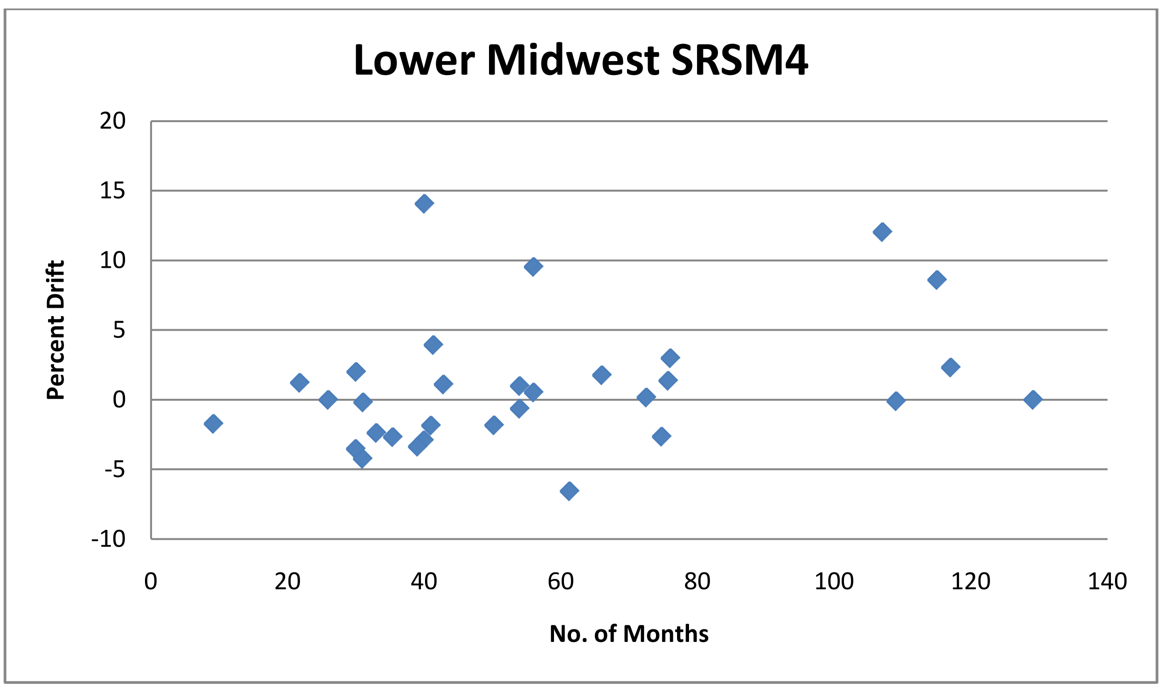


Figure C-26. Plot of Lower Midwest Region SRSM4 percent drift.

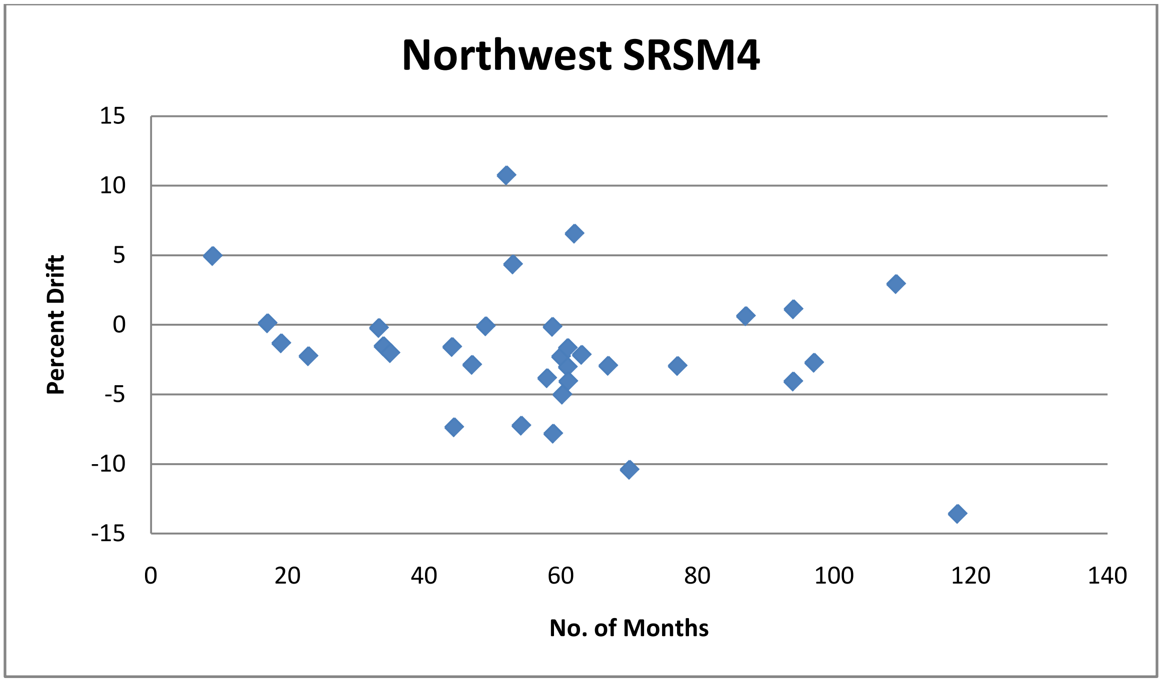


Figure C-27. Plot of Northwest Region SRSM4 percent drift.

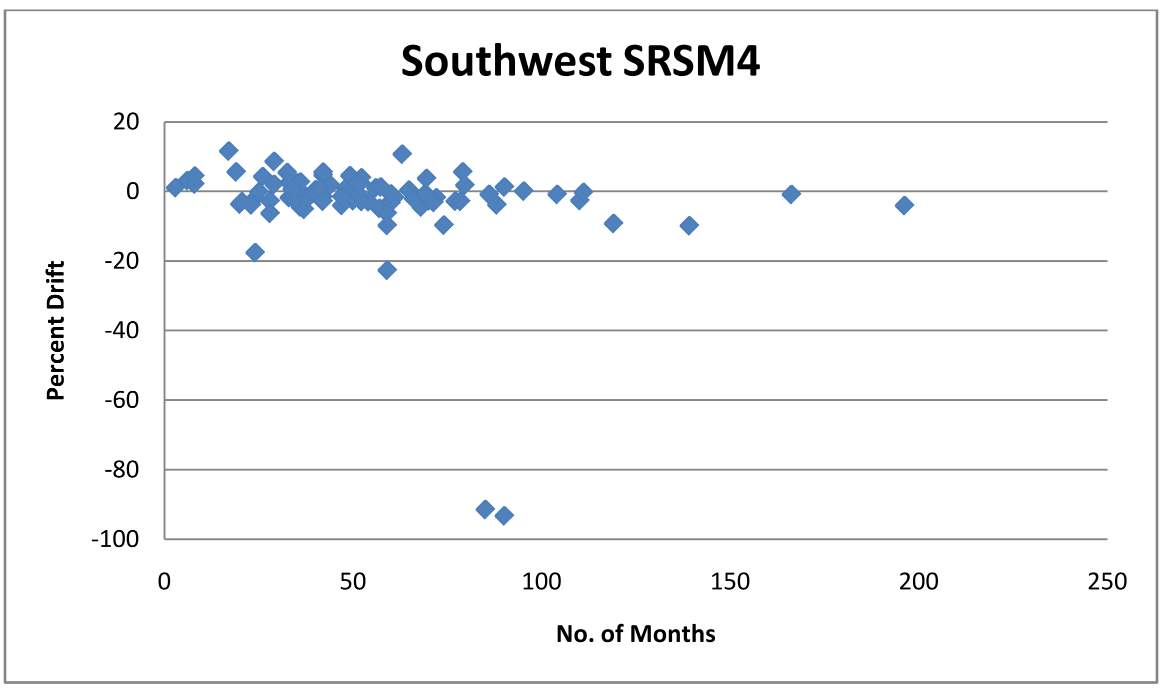


Figure C-28. Plot of Southwest Region SRSM4 percent drift.

SRSM5:

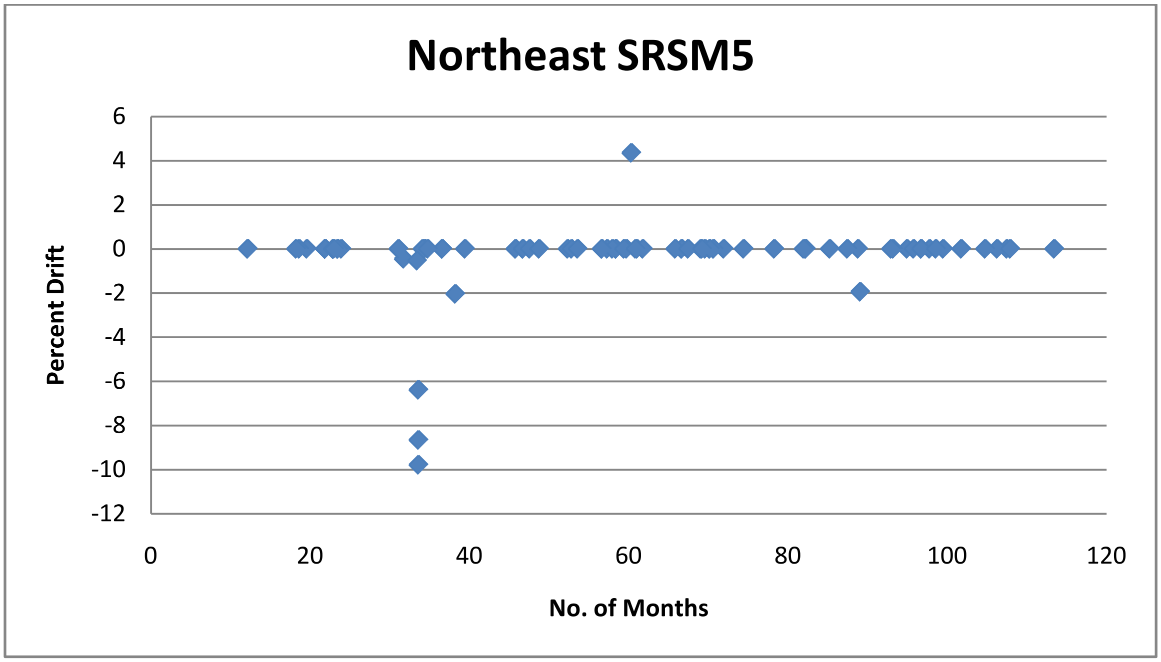


Figure C-29. Plot of Northeast Region SRSM5 percent drift.

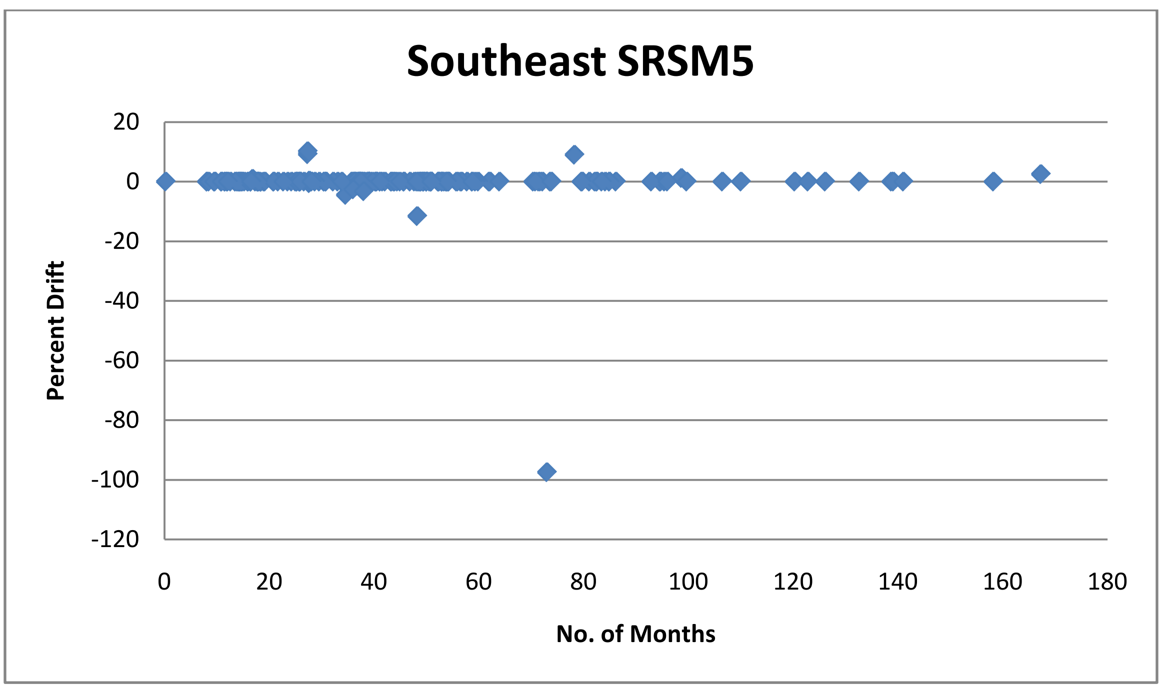


Figure C-30. Plot of Southeast SRSM5 percent drift.

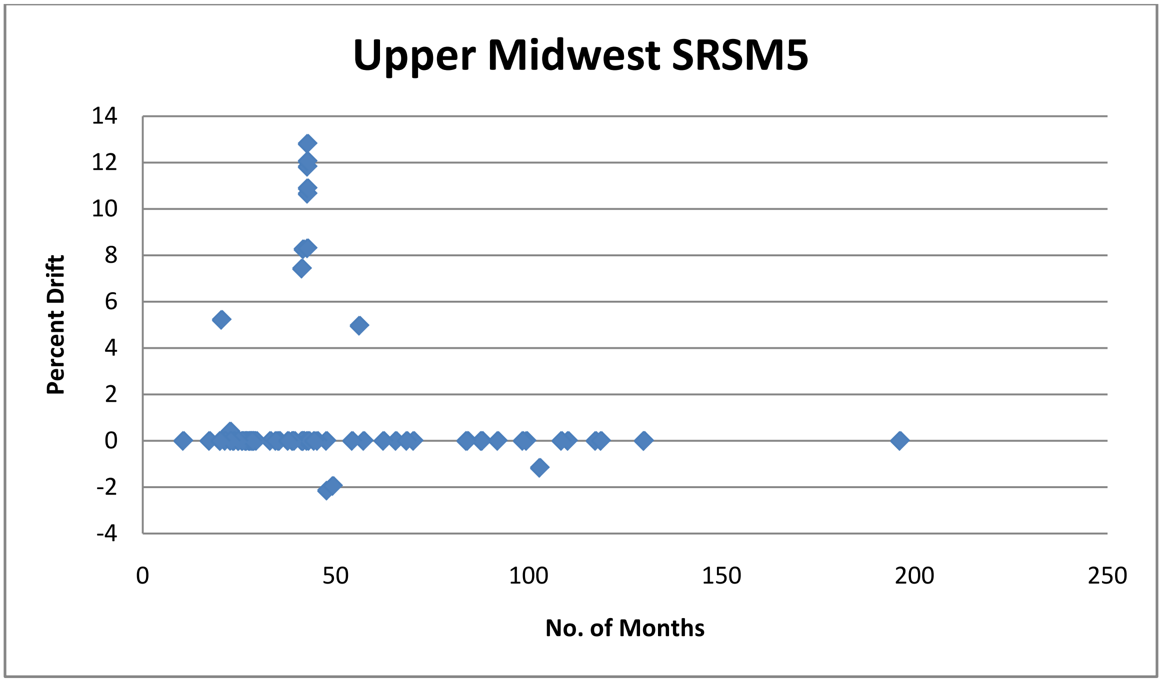


Figure C-31. Plot of Upper Midwest Region SRSM5 percent drift.

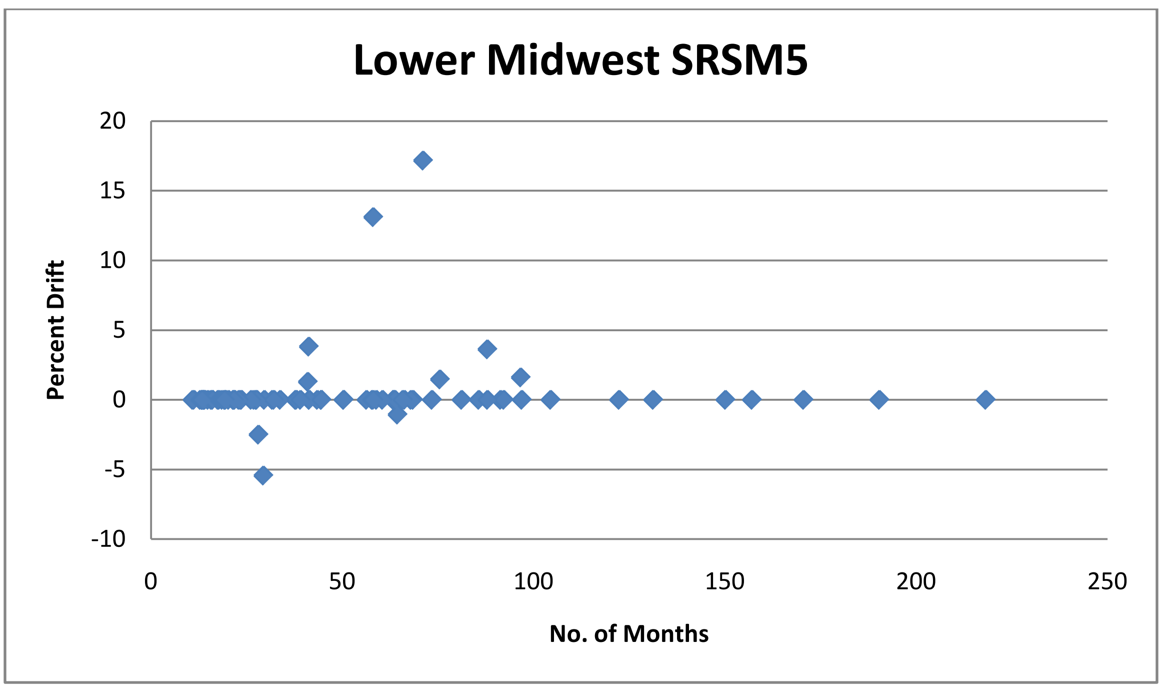


Figure C-32. Plot of Lower Midwest Region SRSM5 percent drift.

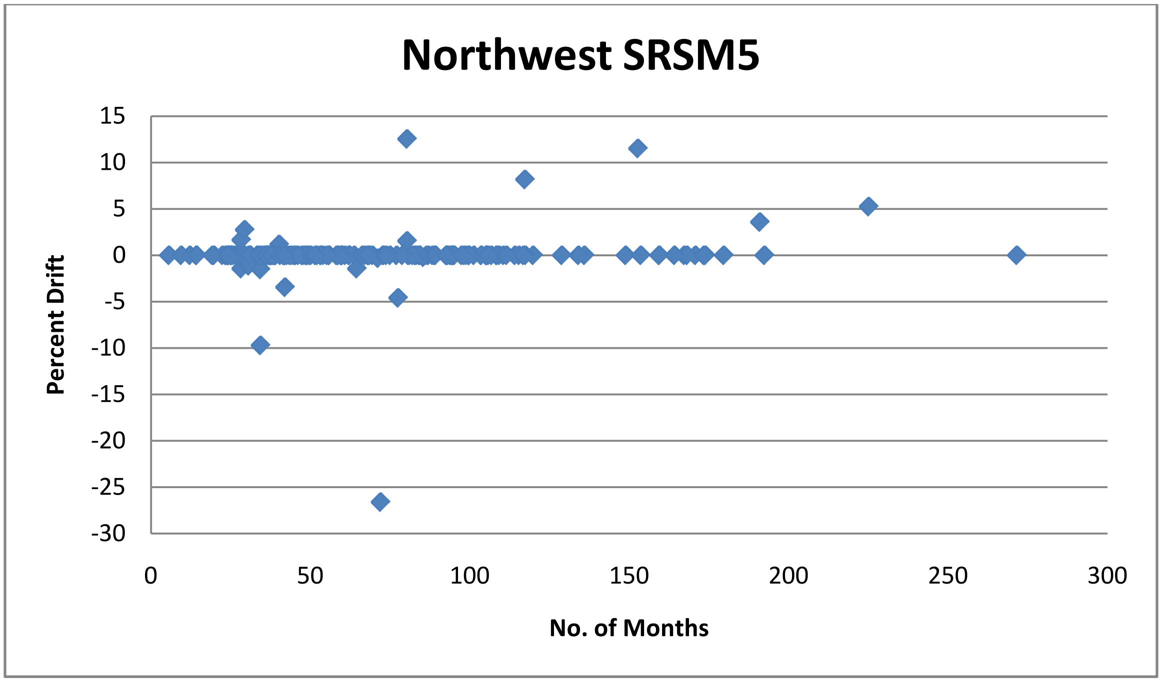


Figure C-33. Plot of Northwest Region SRSM5 percent drift.

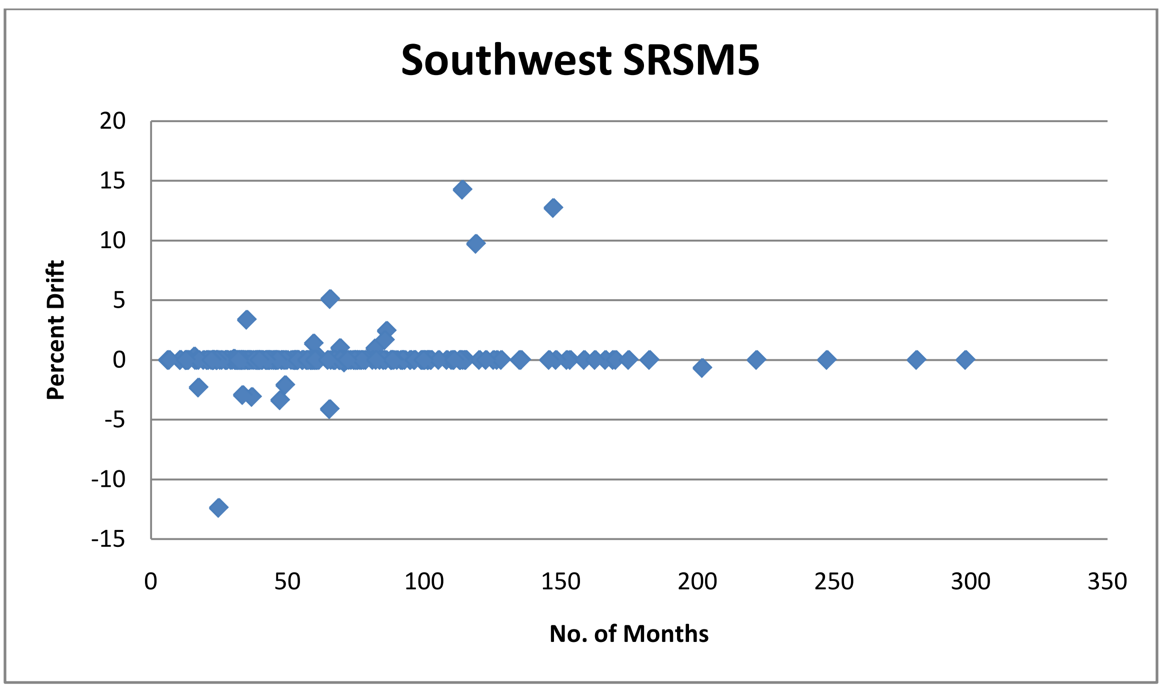


Figure C-34. Plot of Southwest Region SRSM5 percent drift.

Appendix D- Comparison Data Sets/Plots

Weather data from the Crop Weather Program and the iAIMS Climatic Database for Victoria, TX locations included daily data for the dates of August 1, 2010 through August 9, 2010. These two locations both record maximum temperature, minimum temperature, average temperature and wind speed. This particular iAIMS station records wind speed at 10 m (33 ft) and had to be adjusted using the wind speed adjustment algorithm. Looking at each parameter, the maximum temperature had an average difference of 2.61 ^{o}C (7 ^{o}F) with a maximum difference of 6.61 ^{o}C (11.9 ^{o}F) and a minimum difference of 0.06 ^{o}C (0.1 ^{o}F). The average percentage difference between the two sources for maximum temperature was 4.81 percent. The minimum temperature had an average difference of 0.94 ^{o}C (1.7 ^{o}F) with a maximum of 1.94 ^{o}C (3.5 ^{o}F) and a minimum of 0.11 ^{o}C (0.2 ^{o}F). The average percentage difference between these was 2.35 percent. For the average temperature, the average difference was 1.19 ^{o}C (2.15 ^{o}F) with a maximum difference of 3.11 ^{o}C (5.6 ^{o}F) and a minimum difference of 0.06 ^{o}C (0.1 ^{o}F). The average percentage difference for average temperature was 2.55 percent. The wind speed had an average difference of 0.27 m/s (0.60 mph) with a maximum difference of 0.50 m/s (1.12 mph) and a minimum difference of 0.01 m/s (0.02 mph). The average percentage difference for wind speed was 18.43 percent.

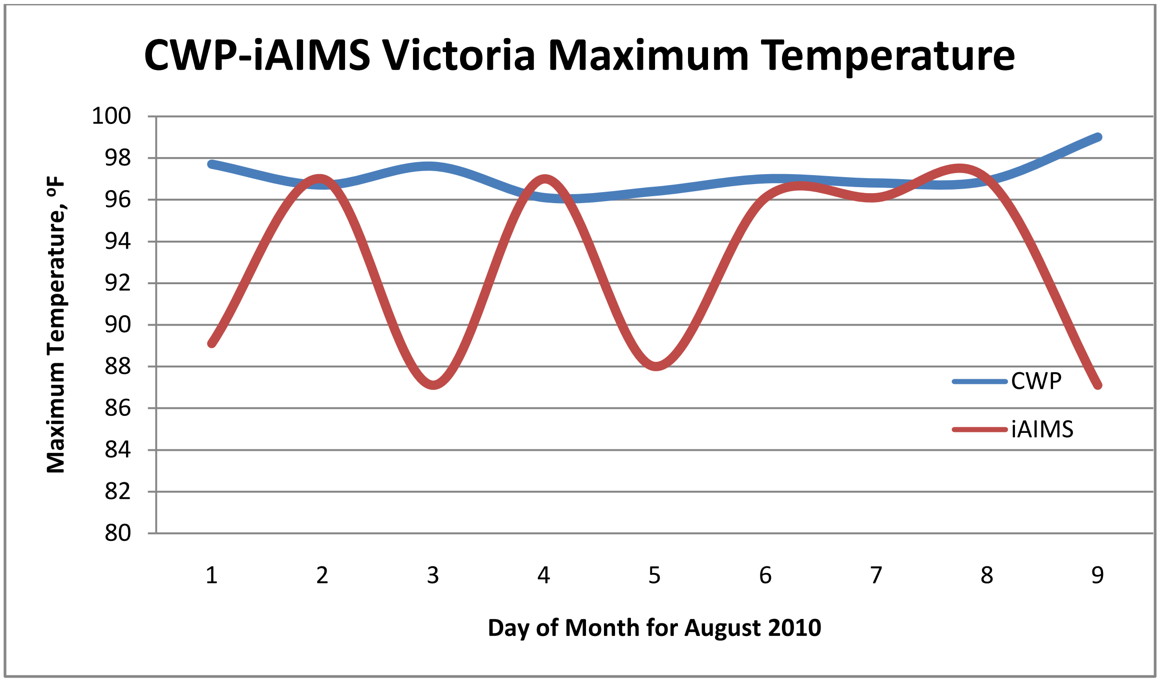


Figure D-1. Plot of Victoria daily data for maximum temperature.

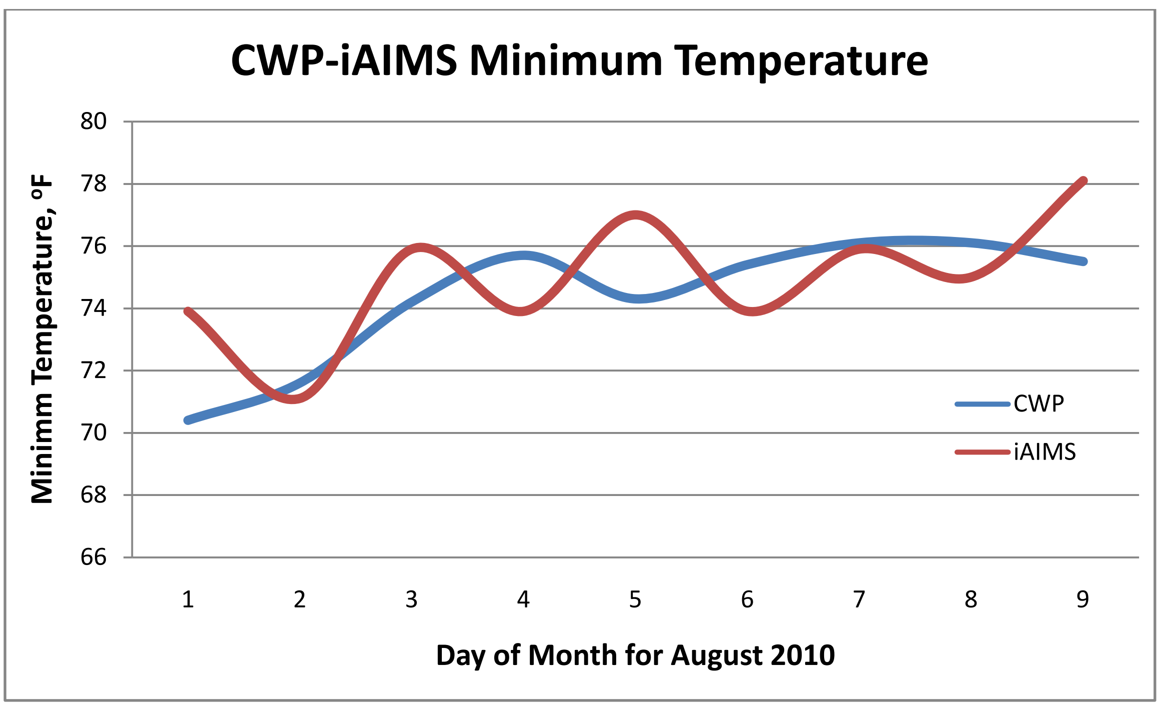


Figure D-2. Plot of Victoria daily data for minimum temperature.

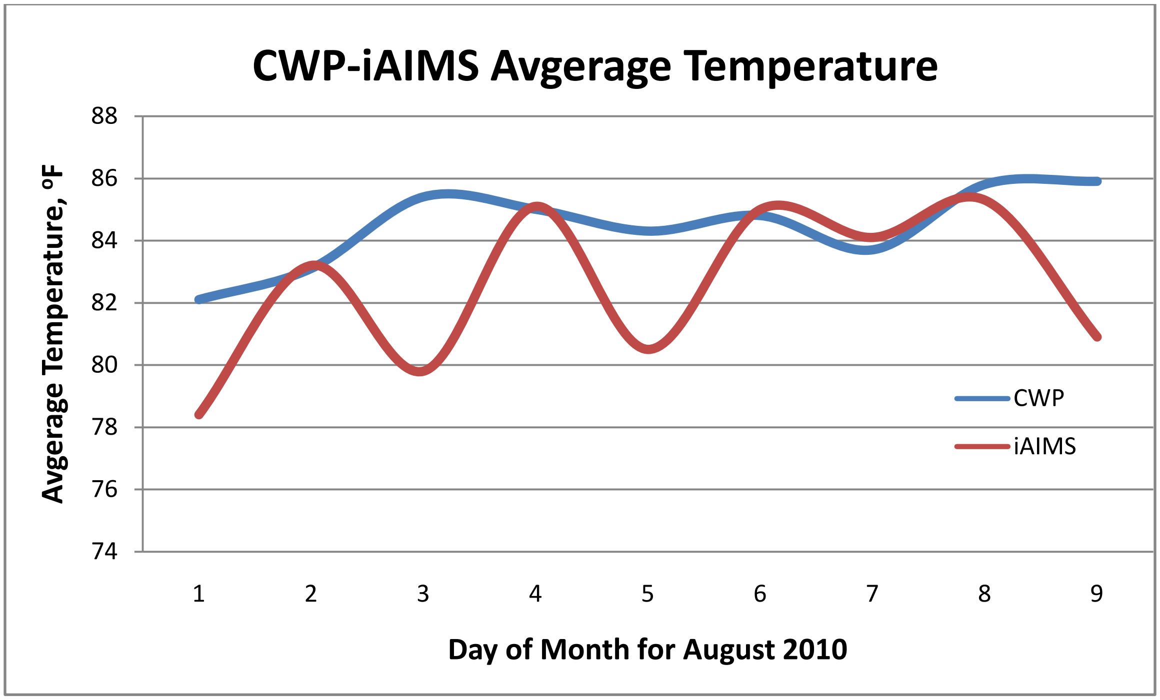


Figure D-3. Plot of Victoria daily data for average temperature.

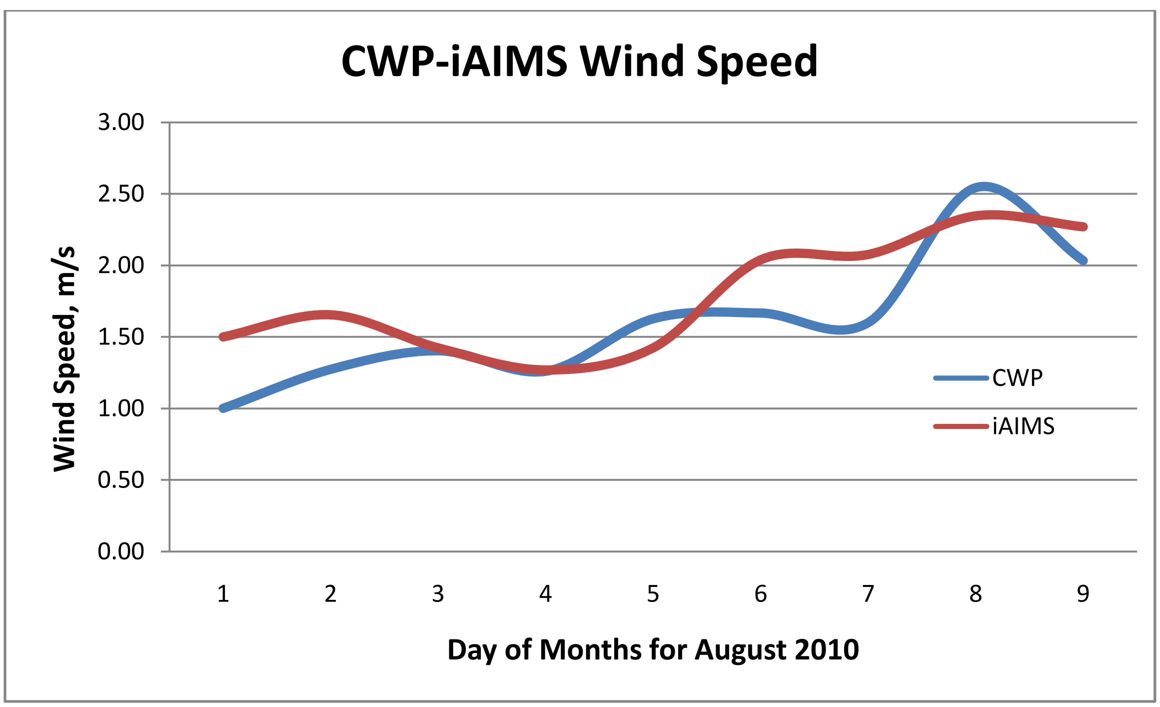


Figure D-4. Plot of Victoria daily data for wind speed.

Data for a Weather Underground station in Victoria was compared with a dataset from the Crop Weather Program for Victoria. This dataset included daily data for the dates of August 1, 2010 through August 9, 2010. These two networks both recorded maximum temperature, minimum temperature, average temperature, relative humidity and wind speed. The Weather Underground station measures wind speed at 10 meters (33 ft) and had to be adjusted using the wind speed adjustment algorithm. The maximum temperature had an average difference of 1.48 ^{o}C (2.67 ^{o}F) with a maximum of 8.11 ^{o}C (14.6 ^{o}F) and a minimum of 0 ^{o}C (0 ^{o}F). The average percentage difference for maximum temperature was 2.74 percent. The average difference in minimum temperature was 0.6 ^{o}C (1.08 ^{o}F) with a maximum of 1.56 ^{o}C (2.8 ^{o}F) and a minimum of 0.22 ^{o}C (0.4 ^{o}F). The average percentage difference was 1.45 percent. For average temperature, the average difference was 0.91 ^{o}C (1.63 ^{o} F) with a maximum difference of 3.56 ^{o}C (6.4 ^{o}F) and a minimum difference of 0.11 ^{o}C (0.2 ^{o}F). The average percentage difference for average temperature was 1.93 percent. For relative humidity, the average difference was 14.02 percent with a maximum difference of 18.1 percent and a minimum difference of 5.2 percent. The average percentage difference for relative humidity was 15.72 percent. For wind speed, the average difference was 3.4 m/s (7.61 mph) with a maximum difference of 5.4 m/s (12.08 mph) and a minimum difference of 2.2 m/s (4.92 mph). The average percentage difference for wind speed was 95.48 percent.

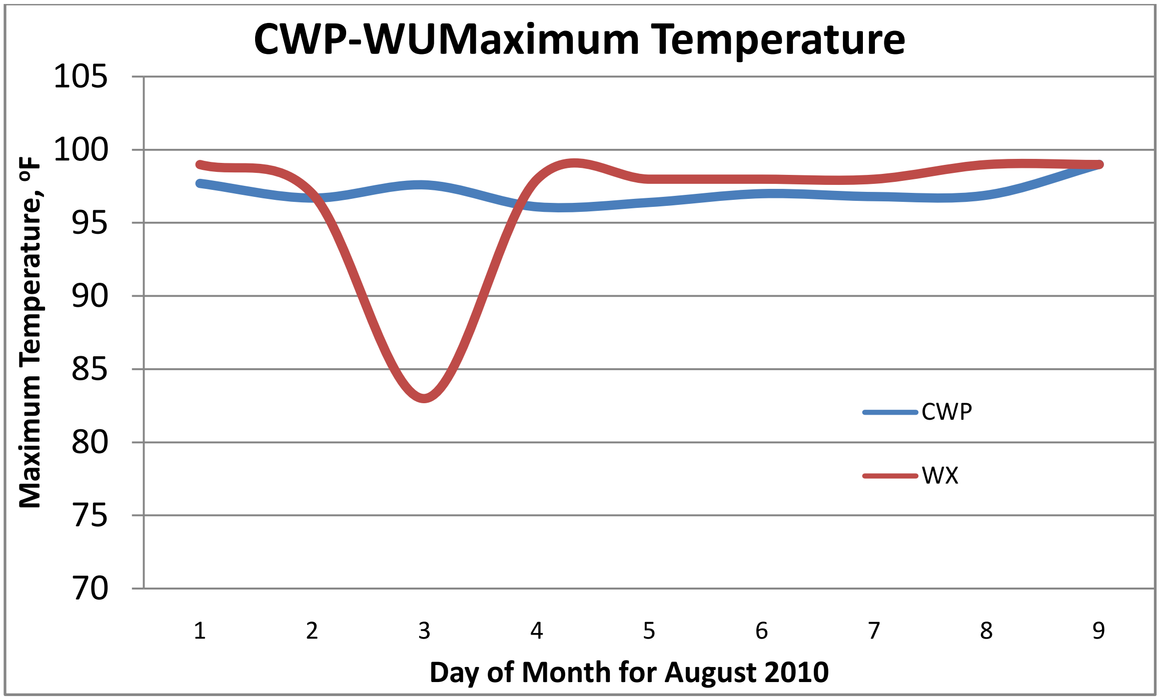


Figure D-5. Plot of Victoria daily data for maximum temperature.

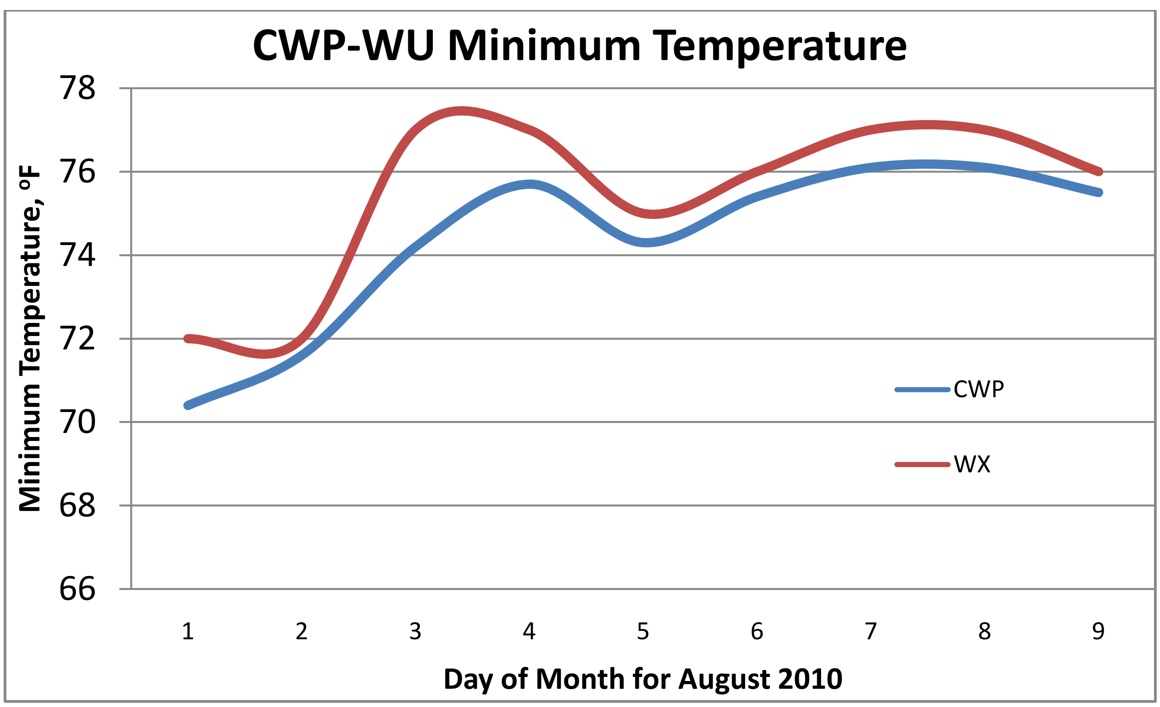


Figure D-6. Plot of Victoria daily data for minimum temperature.

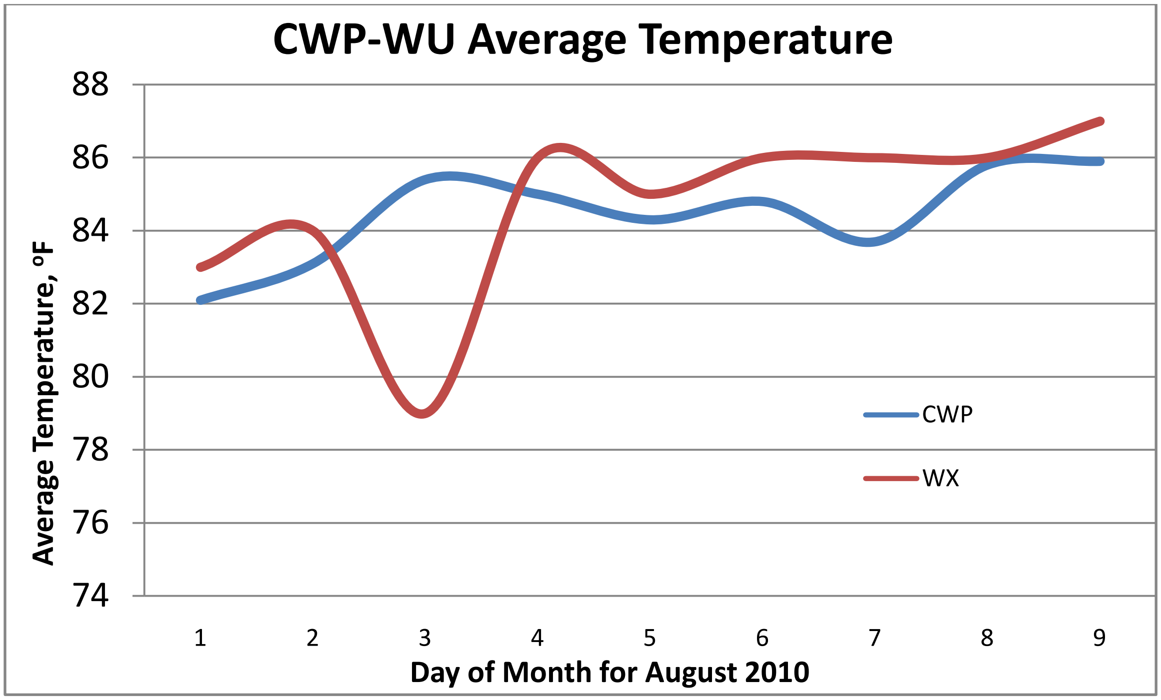


Figure D-7. Plot of Victoria daily data for average temperature.

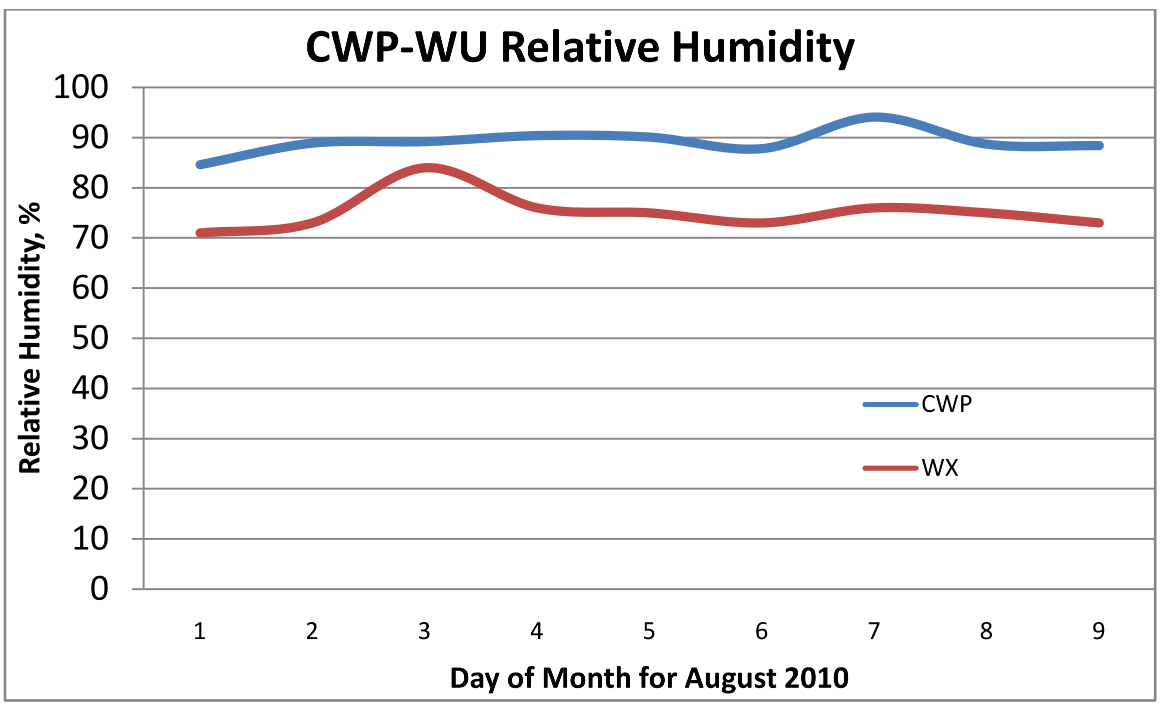


Figure D-8. Plot of Victoria daily data for relative humidity.

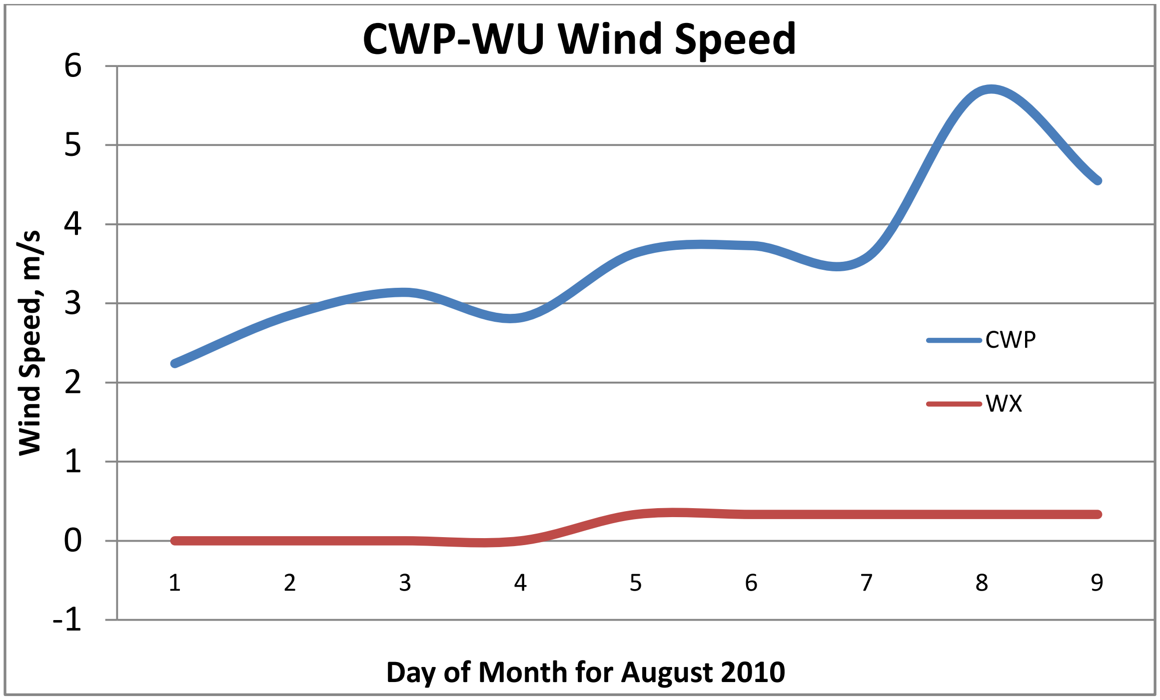


Figure D-9. Plot of Victoria daily data for wind speed.

Next we compared the Texas ET Network and MesoWest station located in Kingwood. This dataset included hourly data for the dates of August 6, 2010 through August 8, 2010. At this location both of these networks collect data for temperature, relative humidity and wind speed. For temperature, the average difference was 1.06 ^{o}C (1.91 ^{o}F) with a maximum difference of 3.78 ^{o}C (6.8 ^{o}F) and a minimum difference of 0 ^{o}C (0 ^{o}F). The average percentage difference for temperature was 2.2 percent. The average difference in relative humidity was 4.71 percent with a maximum difference of 20 percent and a minimum difference of 0 percent. The average percentage difference for relative humidity was 7.16 percent. For wind speed, the average difference was 0.33 m/s (0.74 mph) with a maximum difference of 2.02 m/s (4.52 mph) and a minimum difference of 0. The average percentage difference for wind speed was 78.34 percent.

Of the 50 measurements taken for wind speed, the MesoWest network recorded a zero value for 44 measurements.

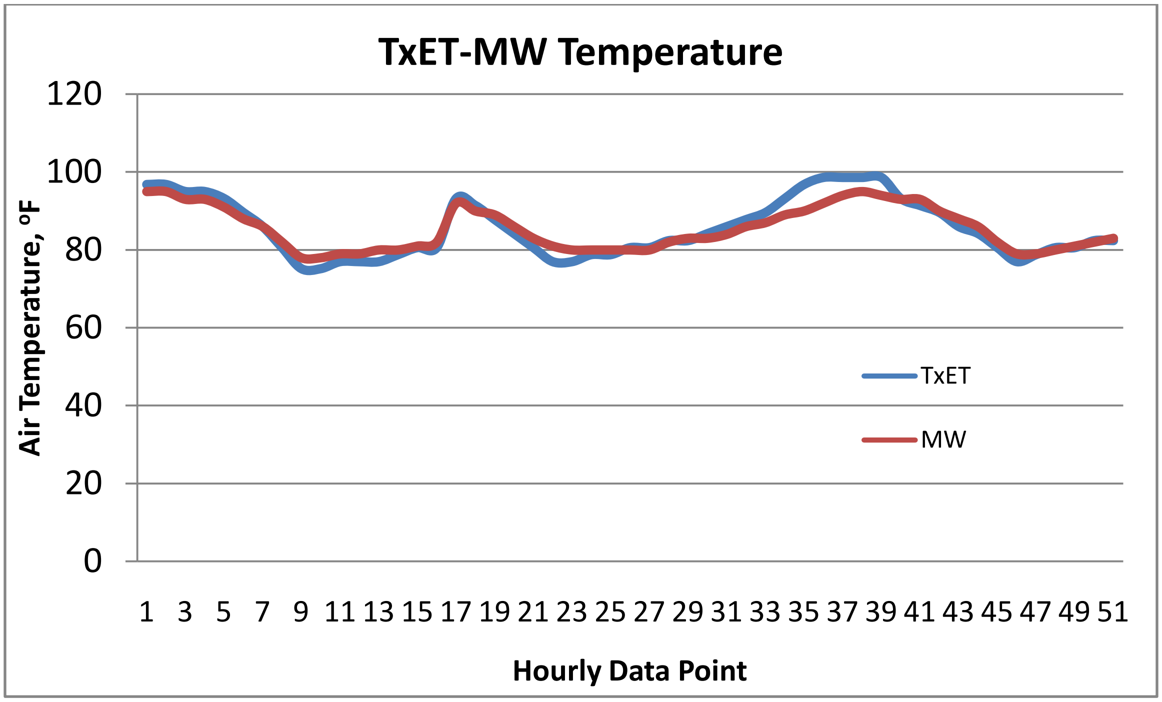


Figure D-10. Plot of Kingwood daily data for air temperature.

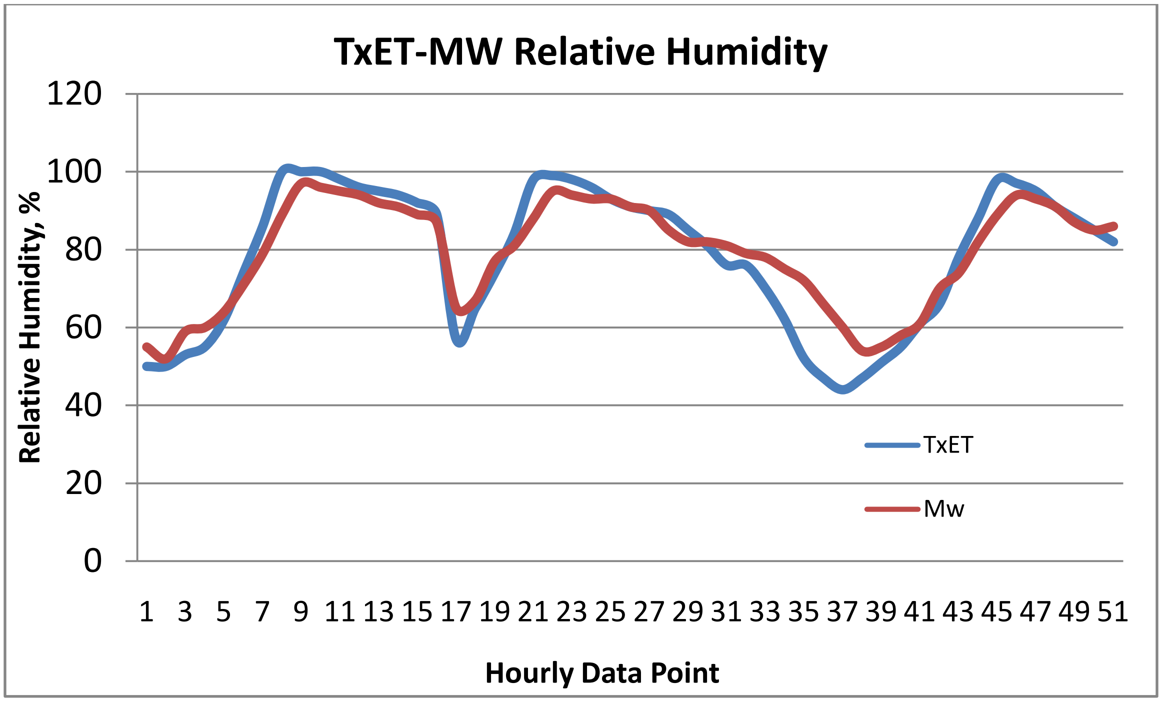


Figure D-11. Plot of Kingwood daily data for relative humidity.

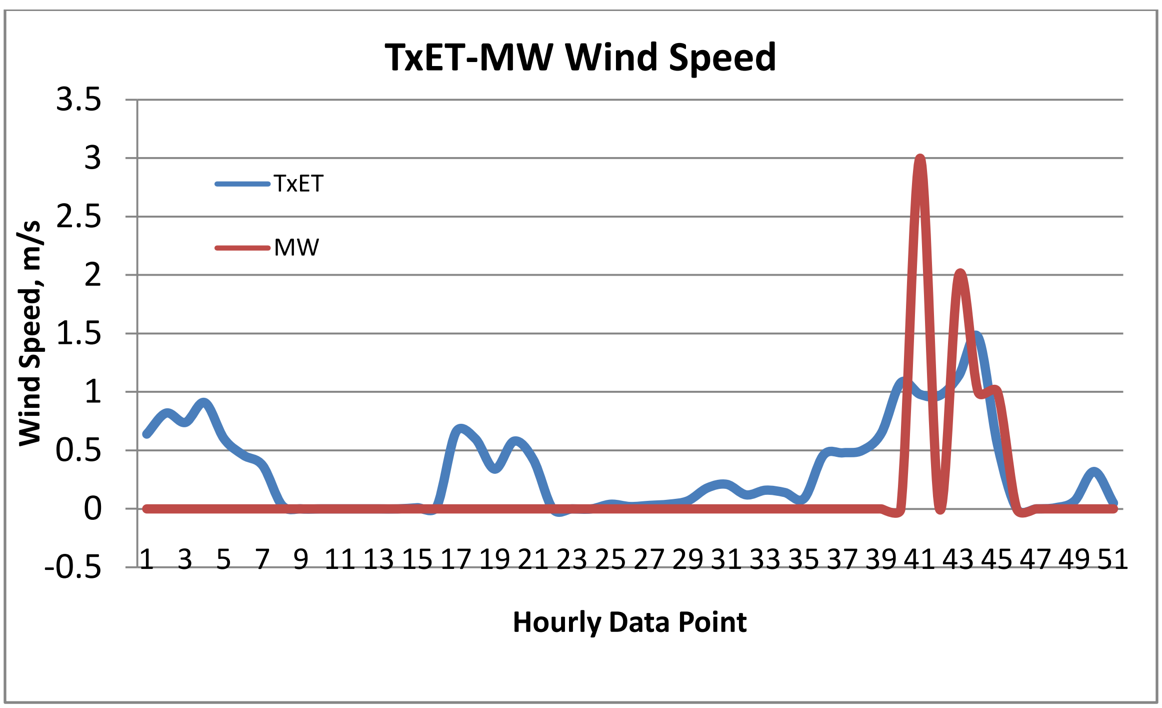


Figure D-12. Plot of Kingwood daily data for wind speed.

Texas ET Network and NCDC data compared for College Station included maximum temperature, minimum temperature and relative humidity. The average difference for maximum temperature was 1.63 ^{o}C (2.93 ^{o}F) with a maximum of 2.22 ^{o}C (4 ^{o}F) and a minimum of 0.89 ^{o}C (1.6 ^{o}F). The average percentage difference was 3.4 percent. For minimum temperature the average temperature was 0.92 ^{o}C (1.65 ^{o}F) with a maximum difference of 2.11 ^{o}C (3.8 ^{o}F) and a minimum difference of 0 ^{o}C (0 ^{o}F). The average percentage difference for minimum temperature was 2.28 percent. The average difference for relative humidity was 5.15 percent with a maximum difference of 11.5 percent and a minimum difference of 0.5 percent. The average percentage difference for relative humidity was 10.11 percent.

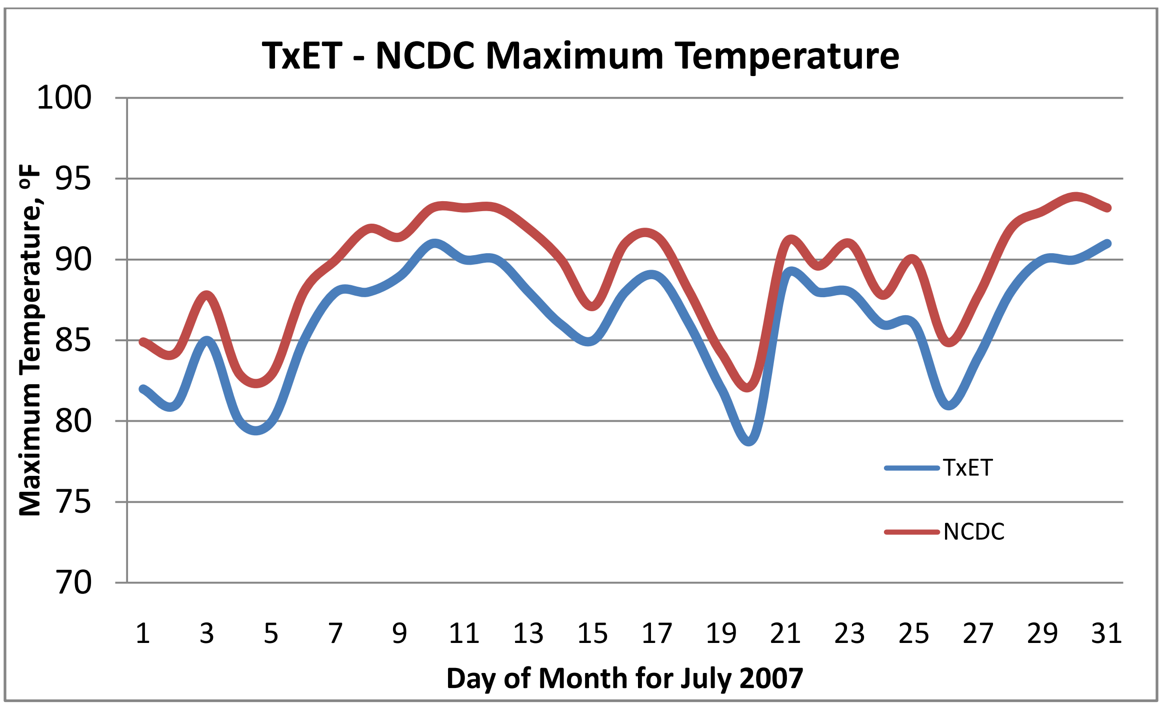


Figure D-13. Plot of College Station daily data for maximum temperature.

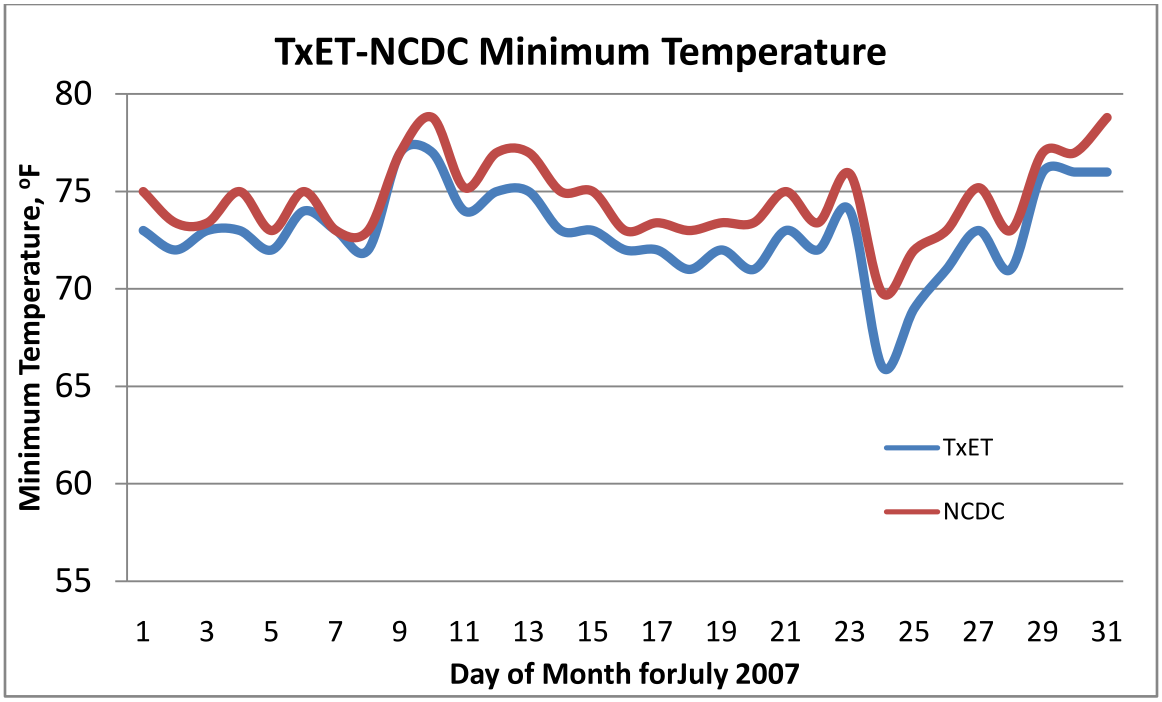


Figure D-14. Plot of College Station daily data for minimum temperature.

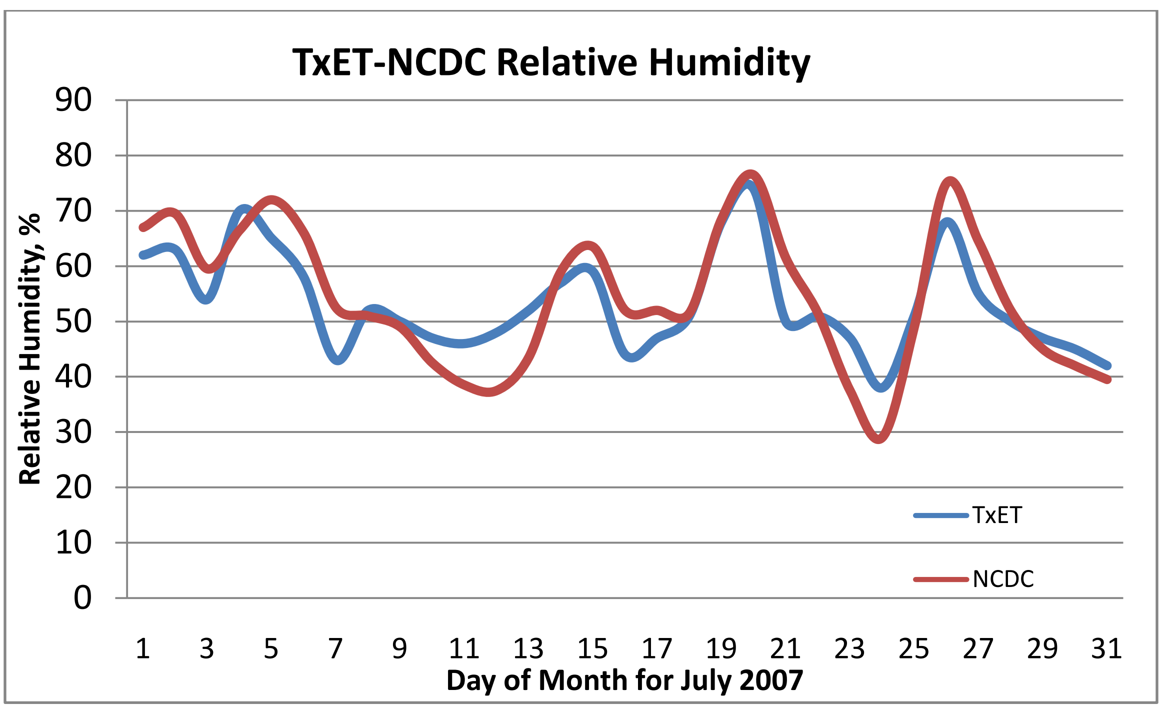


Figure D-15. Plot of College Station daily data for relative humidity.

Compared data from the TXHPET and iAIMS networks included daily values for the month of June 2010 from their respective stations in Bushland. These two stations only shared the measurements of maximum temperature, minimum temperature and rainfall. Due to variations in rainfall between short distances, it was not included in the data comparison. For maximum temperature the average difference was 2.7 ^{o}C (4.86 ^{o}F) with a maximum difference of 6.89 ^{o}C (12.4 ^{o}F) and a minimum difference of 0.17 ^{o}C (0.3 ^{o}F). The average percentage difference was 5.38 percent. The average difference in minimum temperatures was 0.81 ^{o}C (1.45 ^{o}F) with a maximum of 3.39 ^{o}C (6.1 ^{o}F) and a minimum difference of 0.06 ^{o}C (0.1 ^{o}F). The average percentage difference for minimum temperature was 2.29 percent.

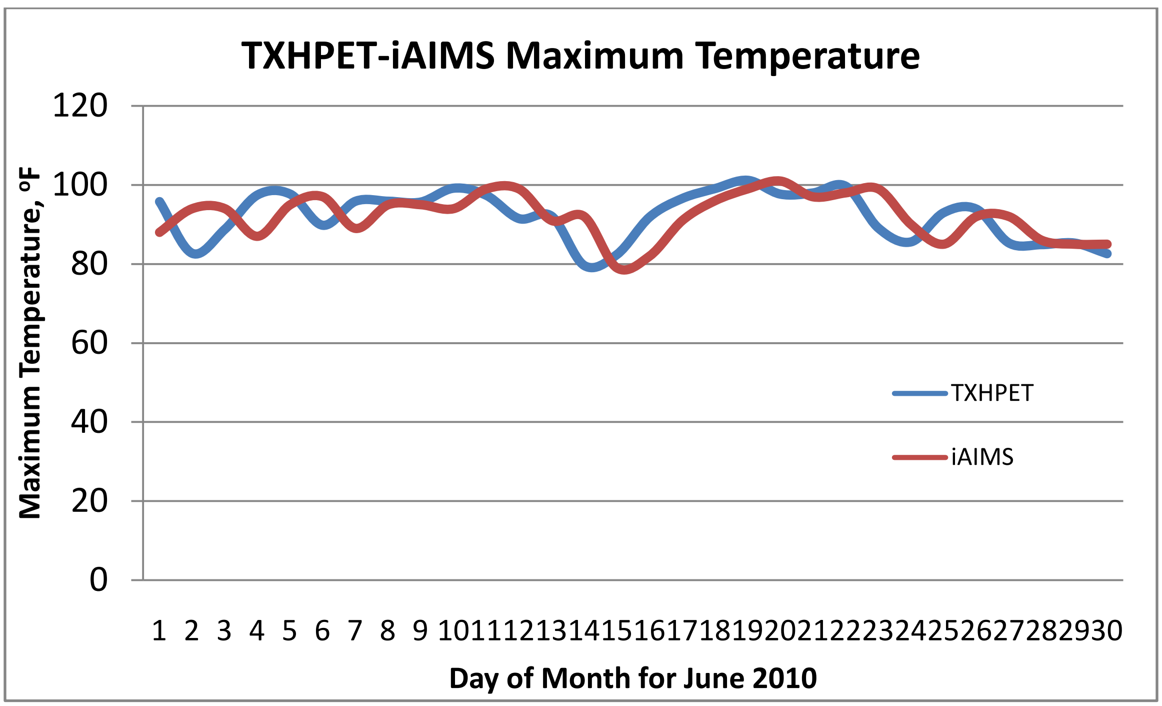


Figure D-16. Plot of Bushland daily data for maximum temperature.

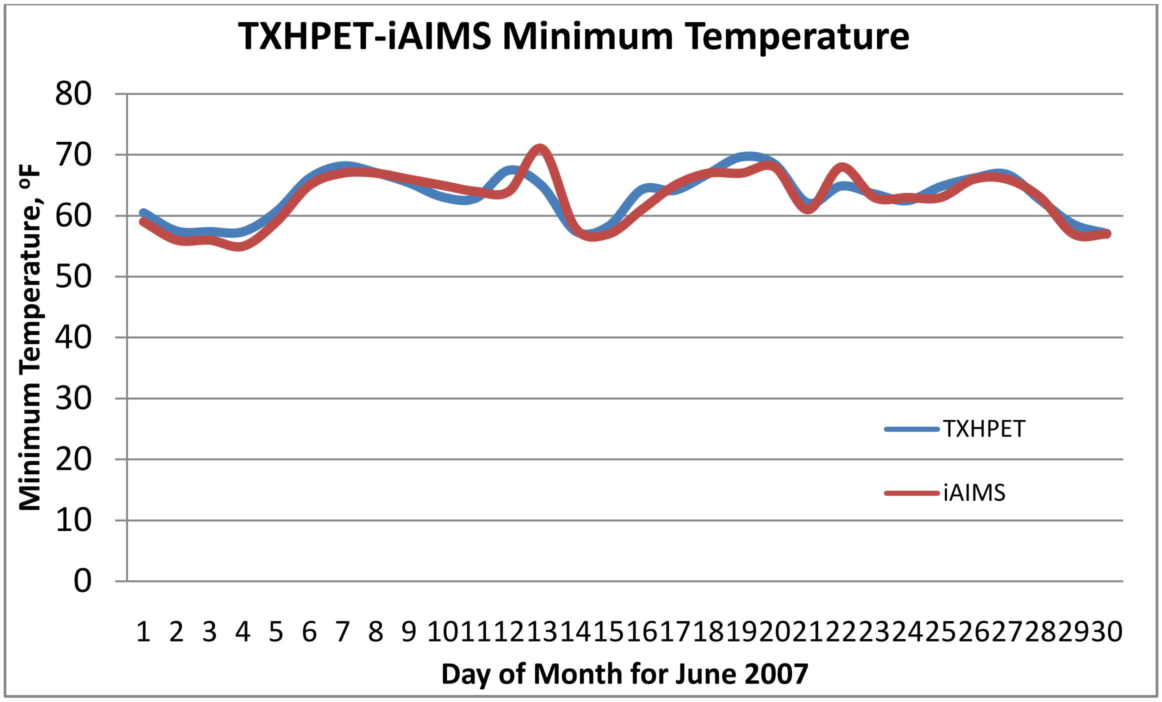


Figure D-17. Plot of Bushland daily data for minimum temperature.

Data from the TXHPET Network and NCDC station at Lubbock included the measurements of average temperature, maximum temperature, minimum temperature, dew point, wind speed and maximum wind speed. The wind speed measurements for the NCDC station were taken at 10 m (33 ft) and were adjusted to 2 m (6.6 ft) using the adjustment algorithm. Beginning with average temperature, the average difference was 0.61 ^oC (1.09 ^oF) with a maximum of 1.56 ^oC (2.8 ^oF) and a minimum of 0.06 ^oC (0.1 ^oF). The average percentage difference for average temperature was 1.44 percent. Moving on to maximum temperature, the average difference was 1.17 ^oC (2.11 ^oF) with a maximum difference of 5.78 ^oC (10.4 ^oF) and a minimum of 0.06 ^oC (0.1 ^oF). The average percentage difference for maximum temperature was 2.43 percent. For minimum temperature, the average difference was 0.83 ^oC (1.49 ^oF) with a maximum difference of 2.78 ^oC (5 ^oF) and a minimum difference of 0.06 ^oC (0.1 ^oF). The average percentage difference for minimum temperature is 2.27 percent. The average difference in dew point temperature was 0.47 ^{o}C (0.84 ^{o}F) with a maximum difference of 1.22 ^{o}C (2.2 ^{o}F) with a minimum difference of 0 ^{o}C (0 ^{o}F). The average percentage difference for dew point was 1.37 percent. For wind speed, the average difference was 0.30 m/s (0.67 mph) with a maximum difference of 0.85 m/s (1.90 mph) with a minimum difference of 0. The average percentage difference for wind speed was 11.38 percent. For maximum wind speed, the average difference was 3.74 m/s (8.37 mph) with a maximum difference of 11.3 m/s (25.28 mph) and a minimum difference of 1.48 m/s (3.31 mph). The average percentage difference for maximum wind speed was 39.26 percent.

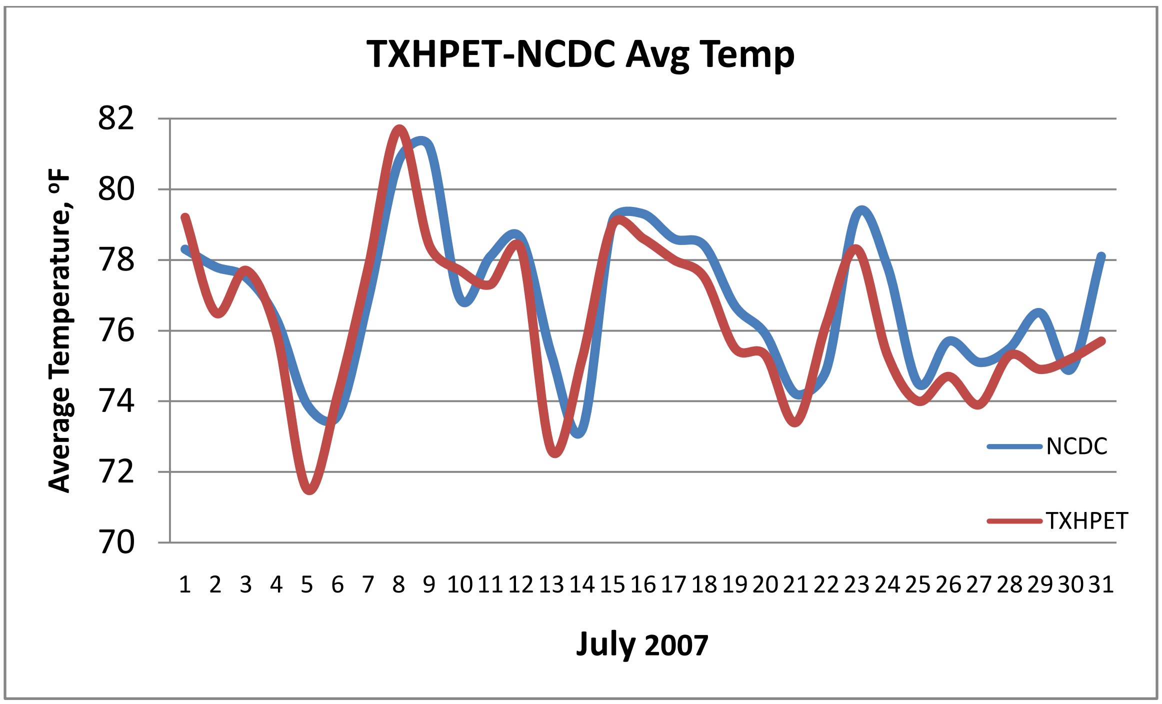


Figure D-18. Plot of Lubbock daily data for average temperature.

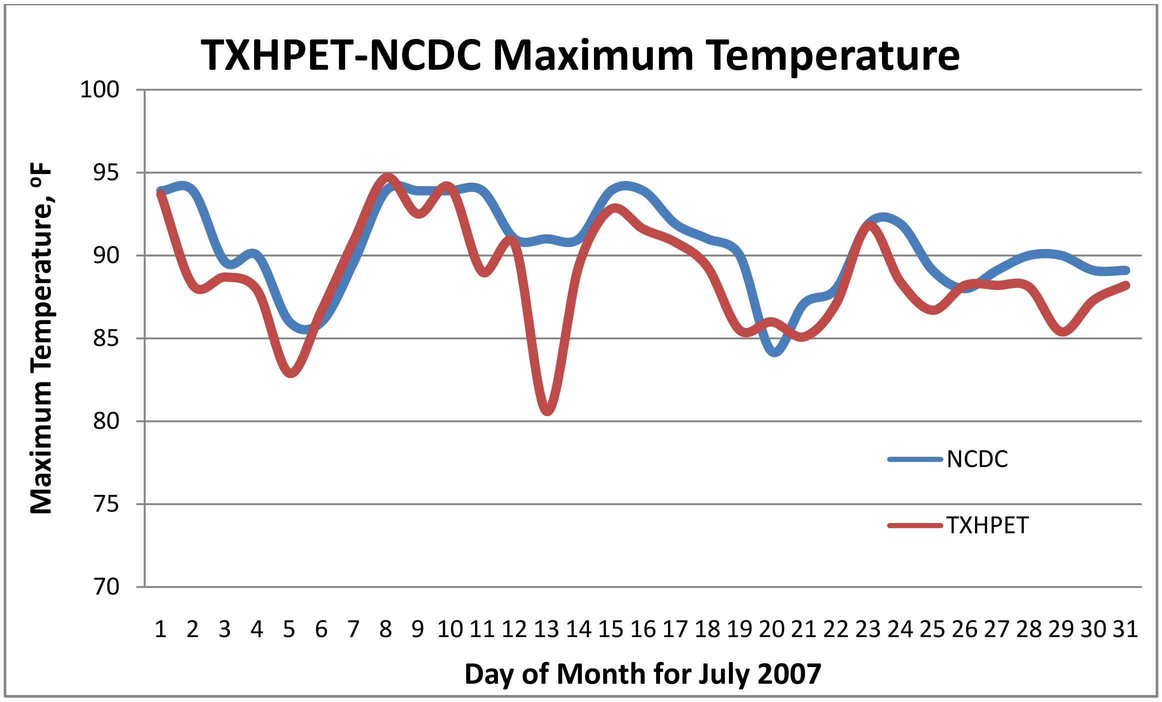


Figure D-19. Plot of Lubbock daily data for maximum temperature.

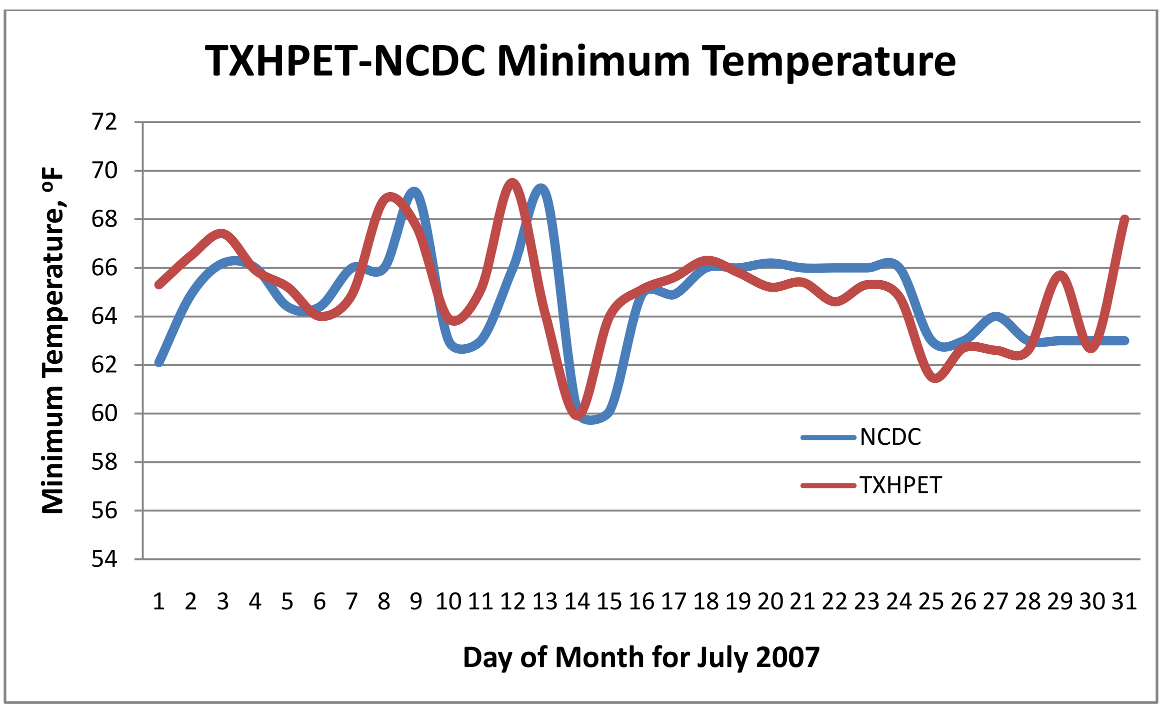


Figure D-20. Plot of Lubbock daily data for minimum temperature.

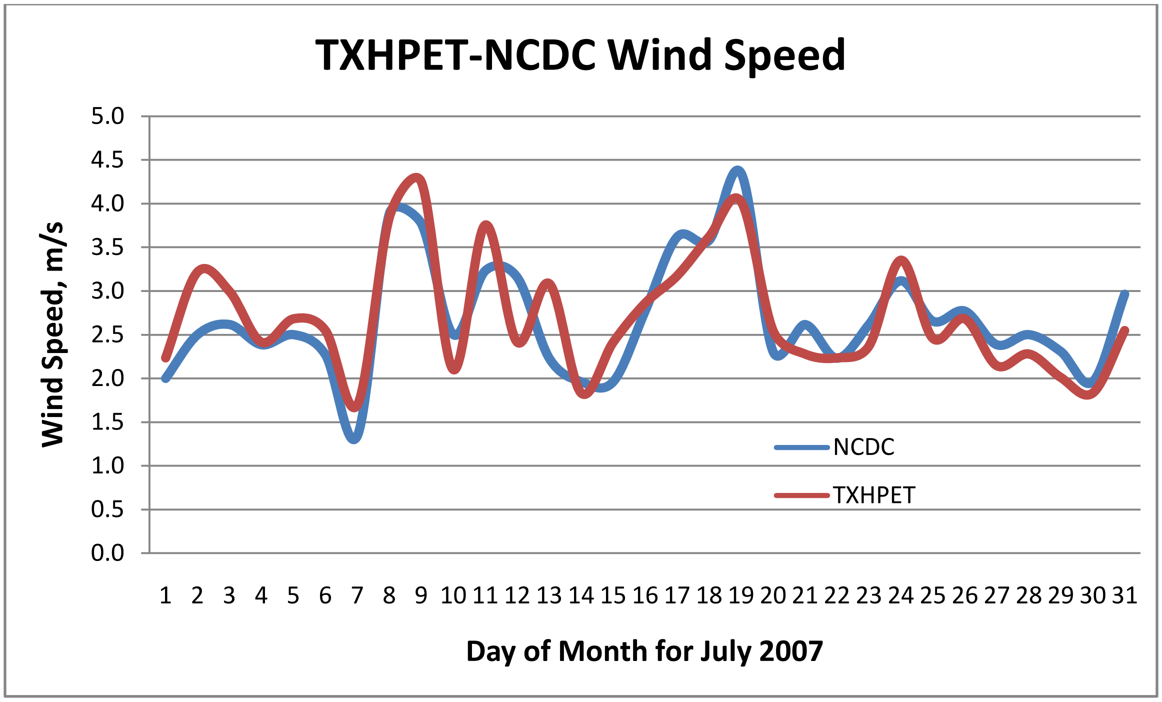


Figure D-21. Plot of Lubbock daily data for wind speed.

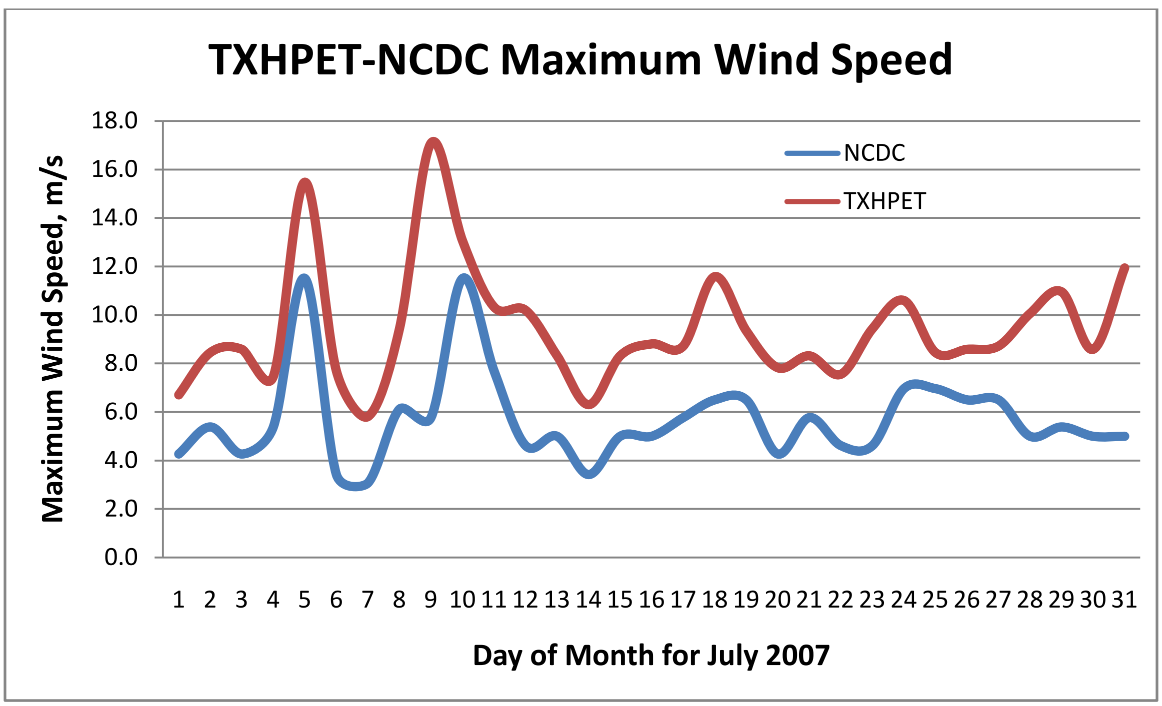


Figure D-22. Plot of Lubbock daily data for maximum wind speed.

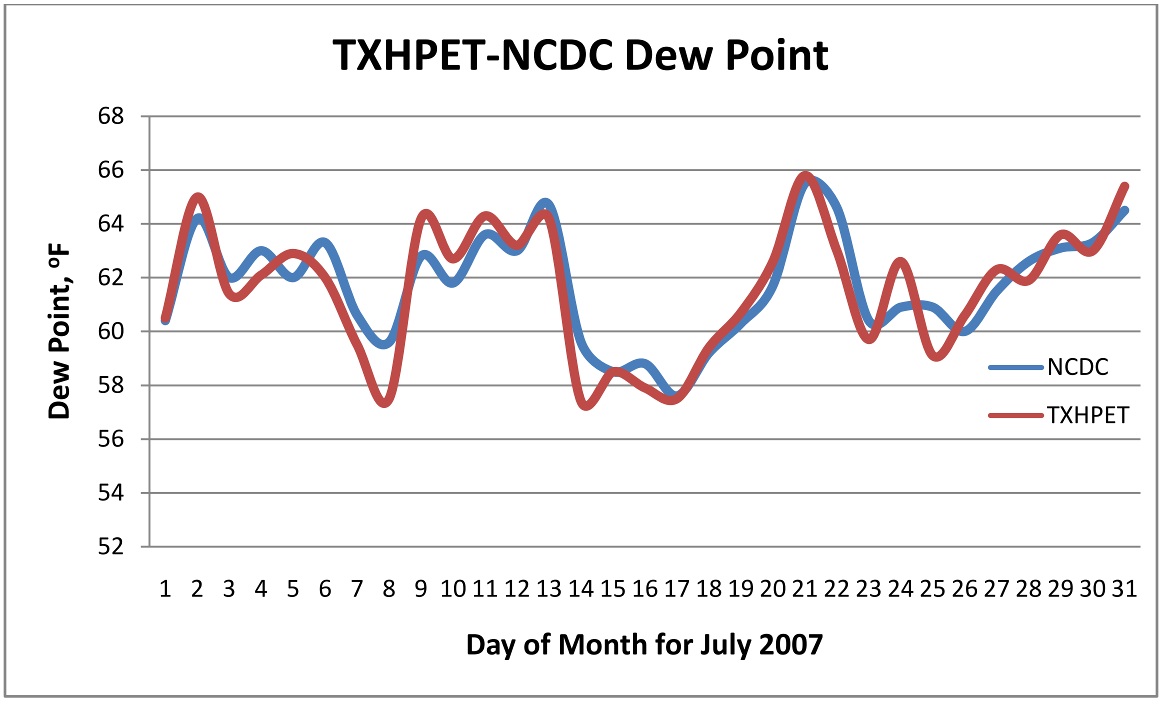


Figure D-23. Plot of Lubbock daily data for dew point.

Hourly data from 26 July 2007 compared from TXHPET network and WTM stations located at Lubbock included relative humidity, air temperature, wind speed and solar radiation. The wind speed for WTM was adjusted from 10 m (33 ft) to 2 m 6.6 ft). The average difference in relative humidity was 4.54 percent with a maximum difference of 10 percent and a minimum difference of 1 percent. The average percentage difference was 7.12 percent. The average difference in air temperature was 1.11 ^{o}C (2 ^{o}F) with a maximum difference of 2.22 ^{o}C (4 ^{o}F) and a minimum difference of 0 ^{o}C (0 ^{o}F). The average percentage difference for air temperature was 2.75 percent. For wind speed, the average difference was 0.79 m/s (1.77 mph) with a maximum difference of 2.58 m/s (5.77 mph) and a minimum difference of zero. The average percentage difference for wind speed was 32.89 percent. The average difference in solar radiation was

100.8 W/m^2 with a maximum difference of 338 W and a minimum difference of 1 W. The average percentage difference for solar radiation was 42.24 percent.

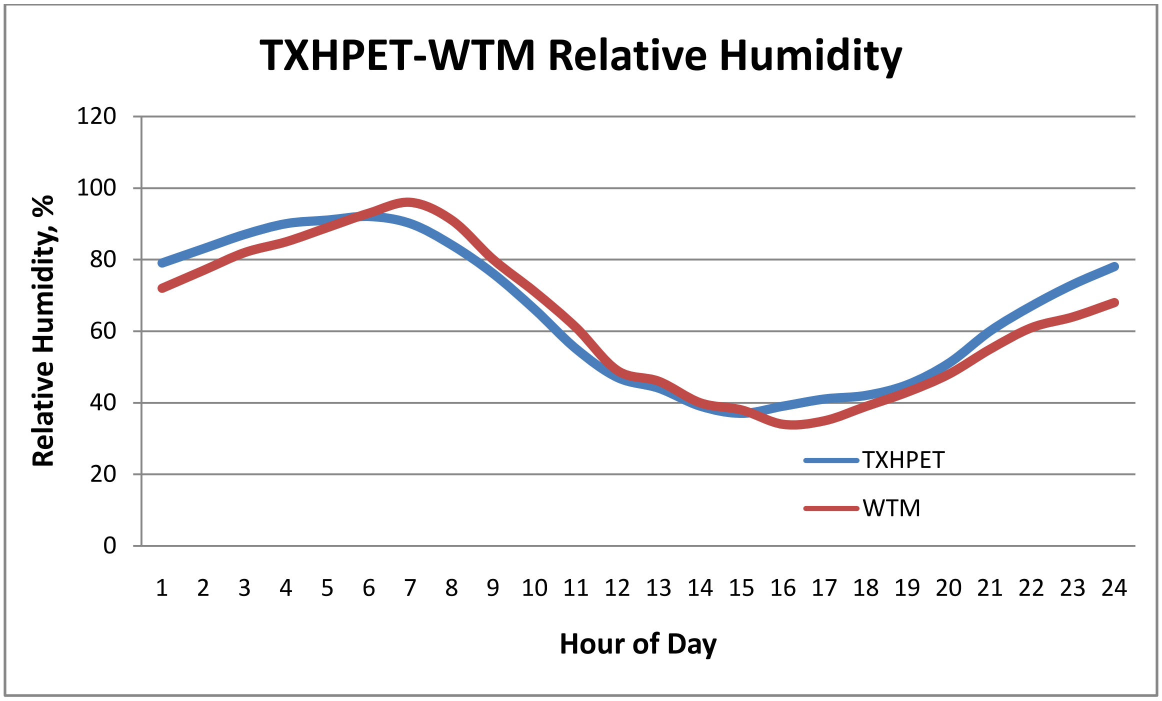


Figure D-24. Plot of Lubbock hourly data for relative humidity.

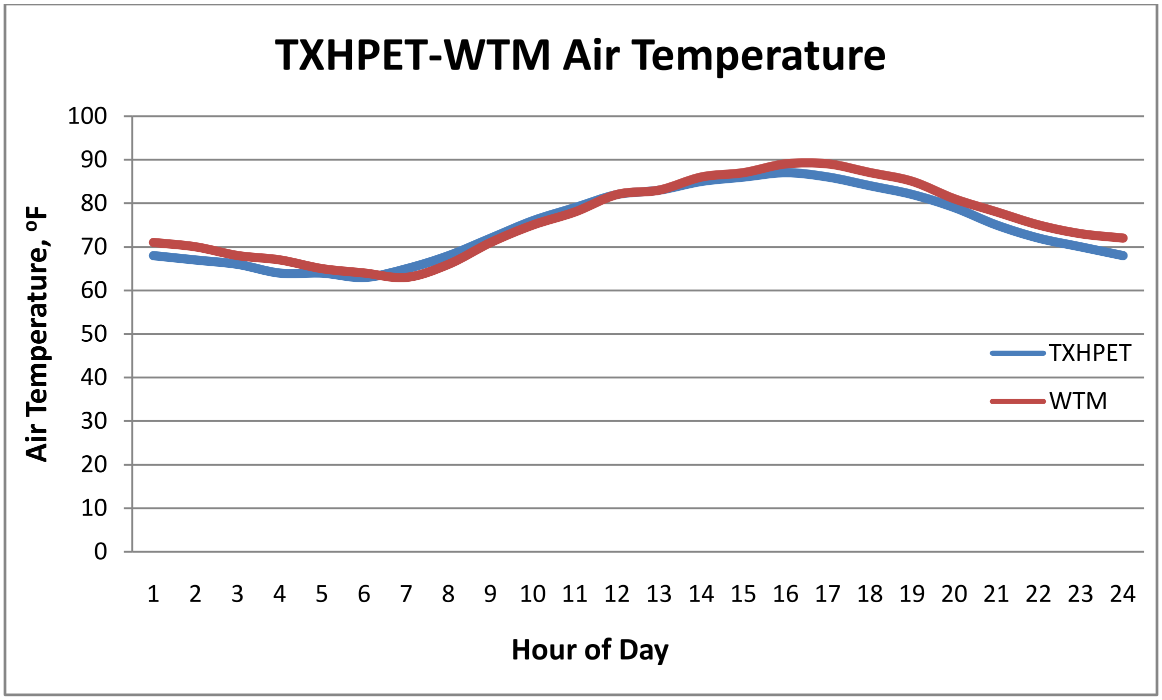


Figure D-25. Plot of Lubbock hourly data for air temperature.

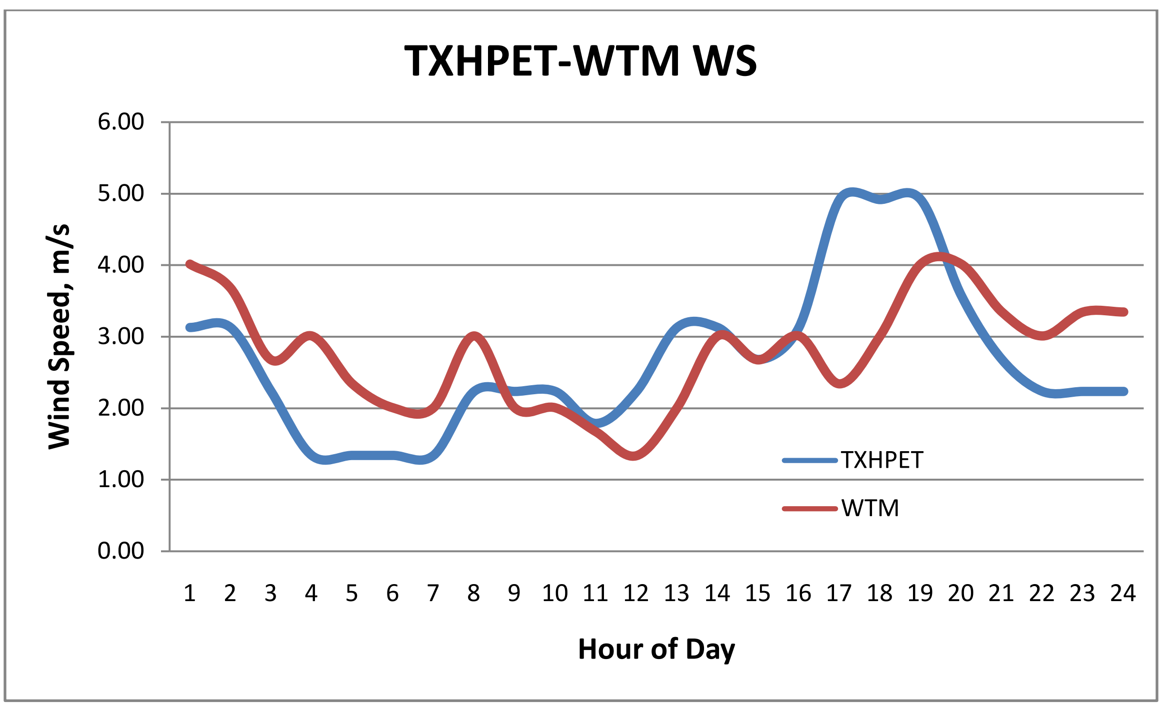


Figure D-26. Plot of Lubbock hourly data for wind speed.

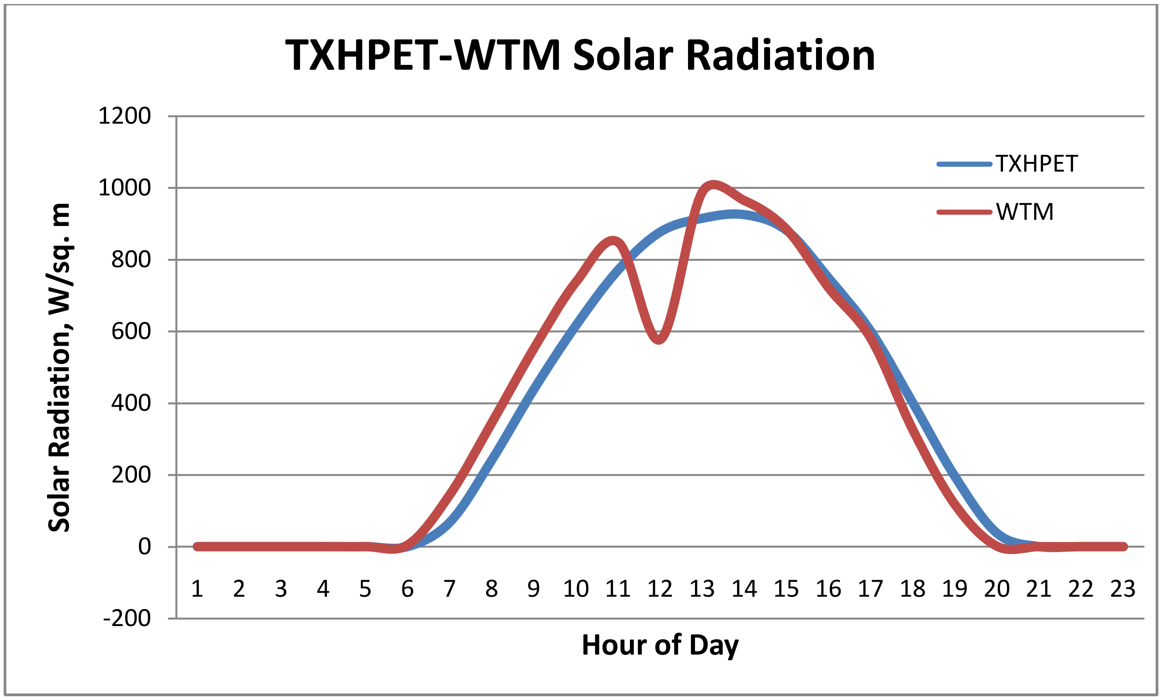


Figure D-27. Plot of Lubbock hourly data for solar radiation.

Compared hourly data from 1 September 2010 from TXHPET network and Weather Underground stations located in Chillicothe included relative humidity, dew point temperature, air temperature and wind speed. The wind speed measurement height is not known for the Weather Underground station. Starting with relative humidity, the average difference in relative humidity was 5.29 percent with a maximum difference of 21 percent and a minimum difference of 1 percent. The average percentage difference of the 24 hourly readings for humidity was 9.17 percent. For dew point temperature, the average difference was 1.35 ^{o}C (2.43 ^{o}F) with a maximum difference of 3.22 ^{o}C (5.8 ^{o}F) and a minimum difference of 0.11 ^{o}C (0.2 ^{o}F). The average percentage difference for dew point temperature was 3.62 percent. Average difference in air temperature was 0.83 ^{o}C (1.49 ^{o}F) with a maximum difference of 3.0 ^{o}C (5.4 ^{o}F) and a minimum difference approaching zero. The average percentage difference for air temperature was 1.83 percent. For wind speed, the average difference was 1.4 m/s (3.13 mph) with a maximum difference of 4.47 m/s (10.0 mph) and a minimum difference of zero. The average percentage difference for wind speed was 46.08 percent.

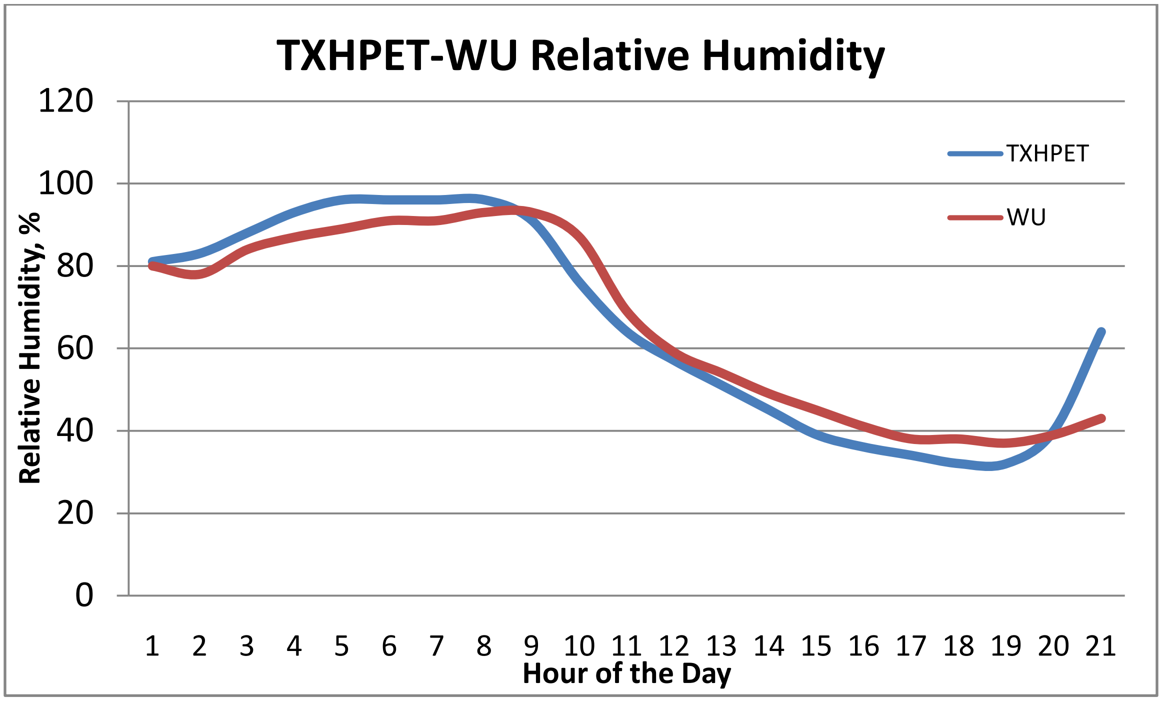


Figure D-28. Plot of Chillicothe hourly data for relative humidity.

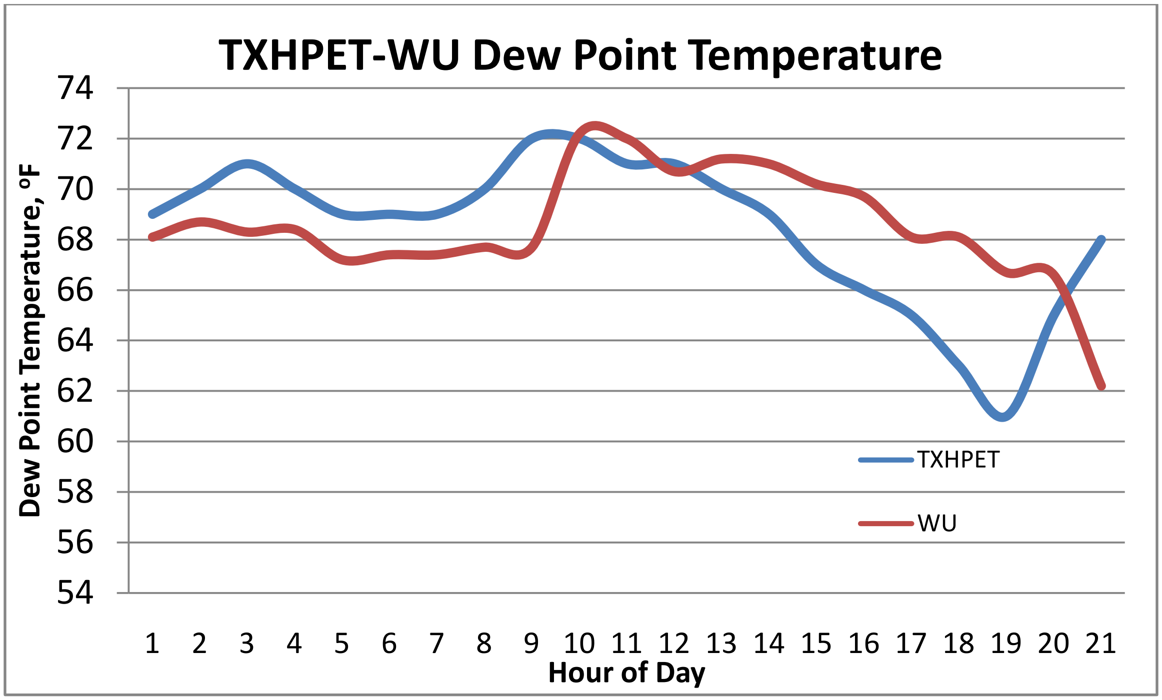


Figure D-29. Plot of Chillicothe hourly data for dew point temperature.

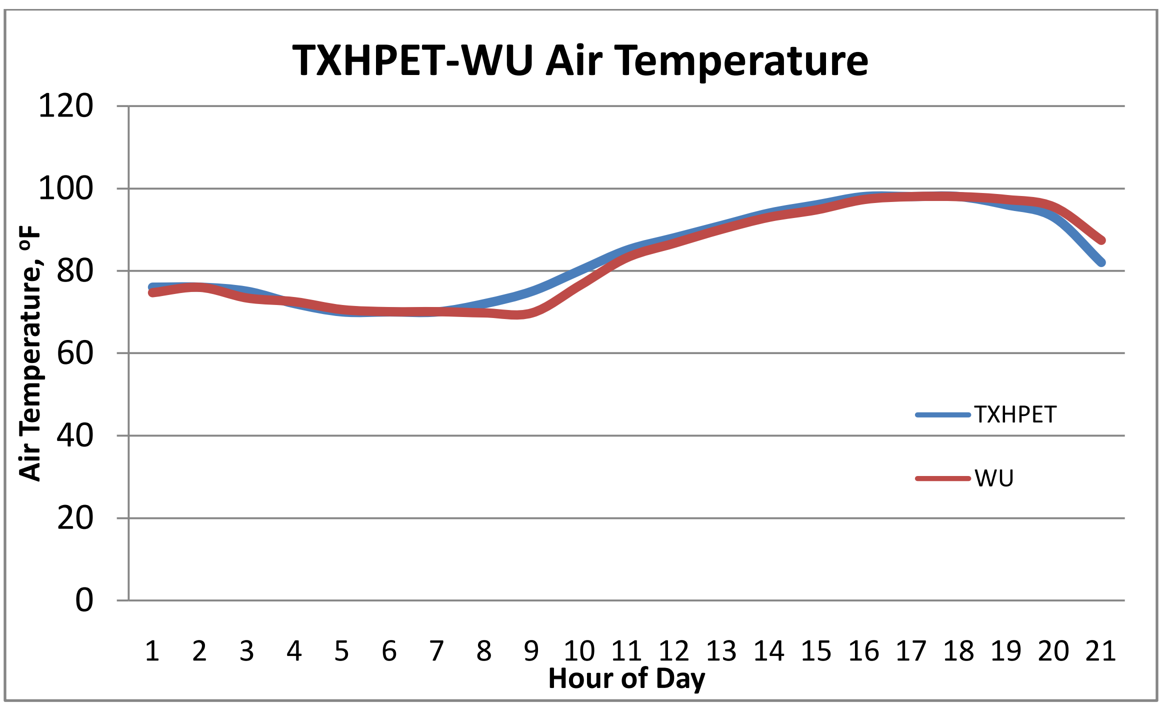


Figure D-30. Plot of Chillicothe daily data for air temperature.

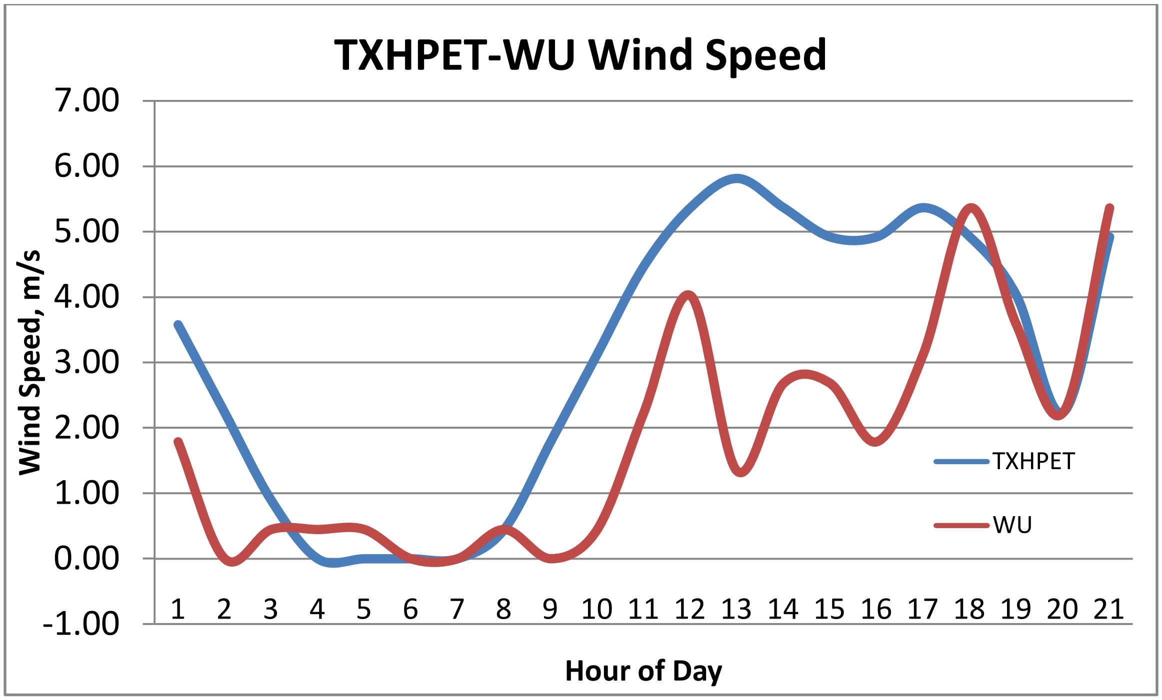


Figure D-31. Plot of Chillicothe daily data for wind speed.

Five-minute data for 10 August 2010 compared from West Texas Mesonet and Weather Underground datasets for their Lubbock stations included temperature, dew point, wind speed, wind gust speed, atmospheric pressure and relative humidity. WTM wind speed measurements are taken at 10 m (33 ft) and adjusted to 2 m (6.6 ft). The wind speed height for the Weather Underground station is unknown and no adjustment was made. Average difference in temperature was 1.88 ^{o}C (3.39 ^{o}F) with a maximum difference of 5.78 ^{o}C (10.4 ^{o}F) and a minimum difference of 0 ^{o}C (0 ^{o}F). The average percentage difference was 4.30 percent. For dew point, the average difference was 1.03 ^{o}C (1.85 ^{o}F) with a maximum difference of 2.78 ^{o}C (5 ^{o}F) and a minimum of 0 ^{o}C (0 ^{o}F). The average percentage difference was 2.36 percent. Average difference in wind speed was 1.85 m/s (4.14 mph) with a maximum difference of 4.01 m/s (8.97 mph) and a minimum difference of 0 m/s (0 mph). The average percentage difference was 86.18 percent. One important note for wind speed is that the WTM station only recorded 1 value of 0 while the Weather Underground station recorded 167 measurements with a value of zero. For wind gust speed, the average difference was 2.4 m/s (5.37 mph) with a maximum difference of 6.91 m/s (15.46 mph) and a minimum difference of 0.11 m/s (0.25 mph). The average percentage difference for gust speed was 78.4 percent. For atmospheric pressure, the average difference was 0.02 inches of mercury with a maximum difference of 0.05 inches and a minimum difference near zero. The average percentage difference for pressure was 0.08 percent. Ending with relative humidity, the average difference was 8.14 percent with a maximum difference of 18 percent and a minimum difference of 0. The average percentage difference for humidity was 13.50 percent.

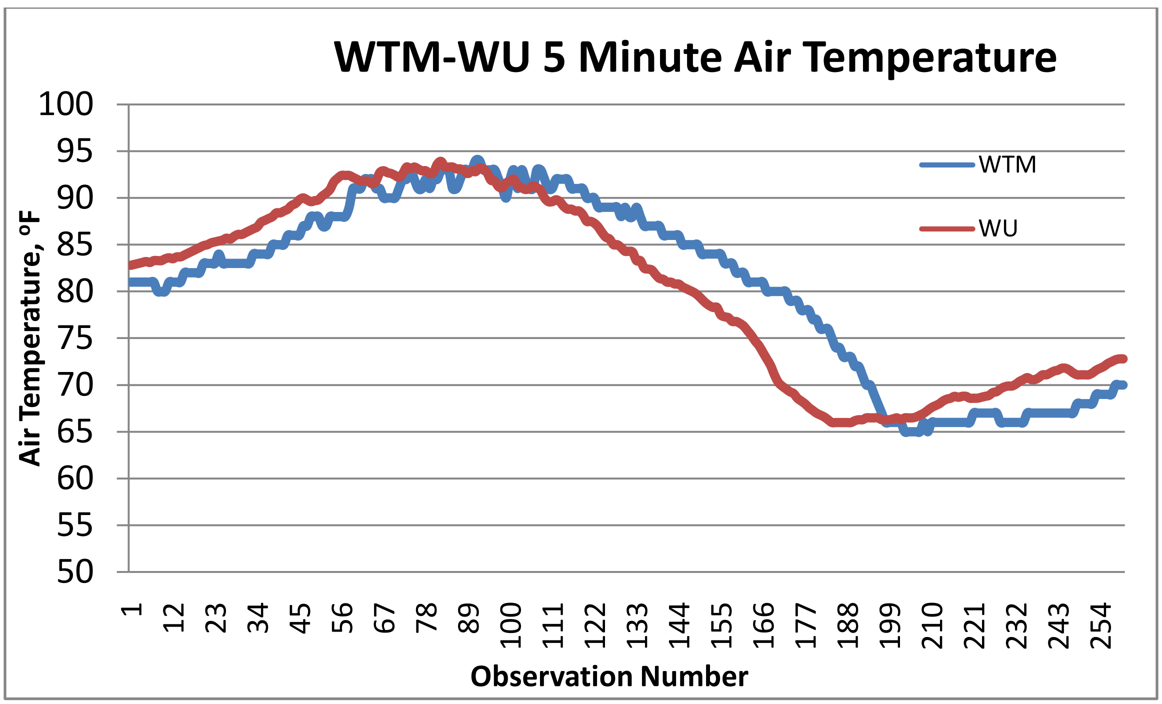


Figure D-32. Plot of Lubbock 5 minute data for air temperature.

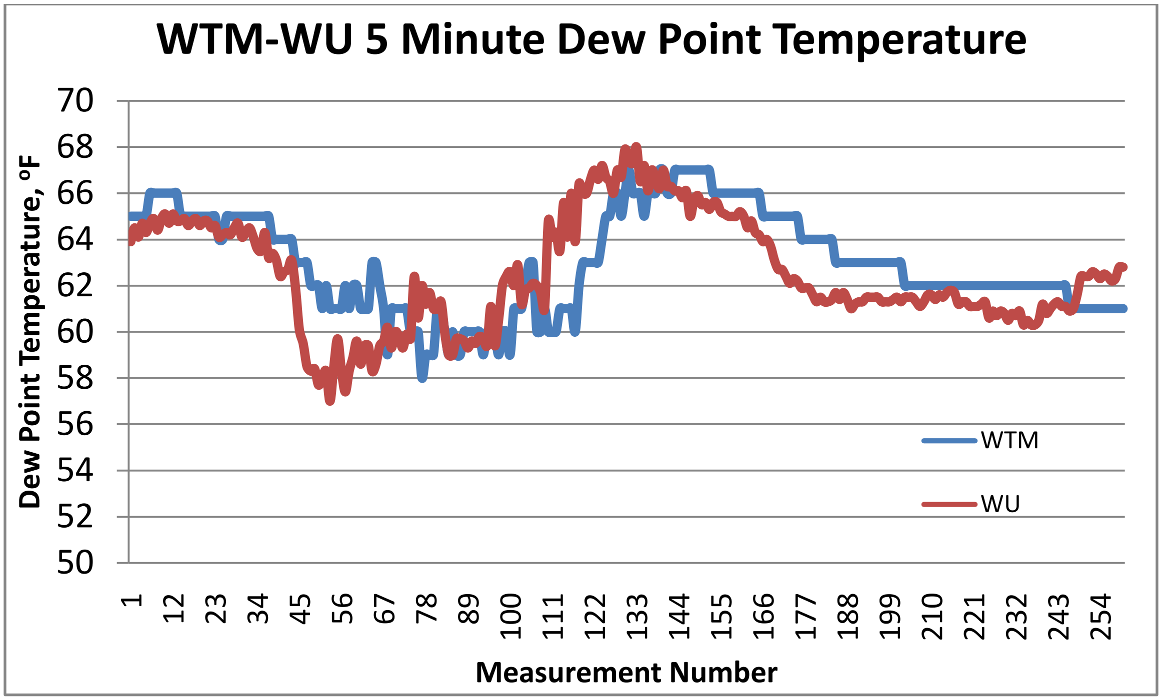


Figure D-33. Plot of Lubbock 5 minute data for dew point temperature.

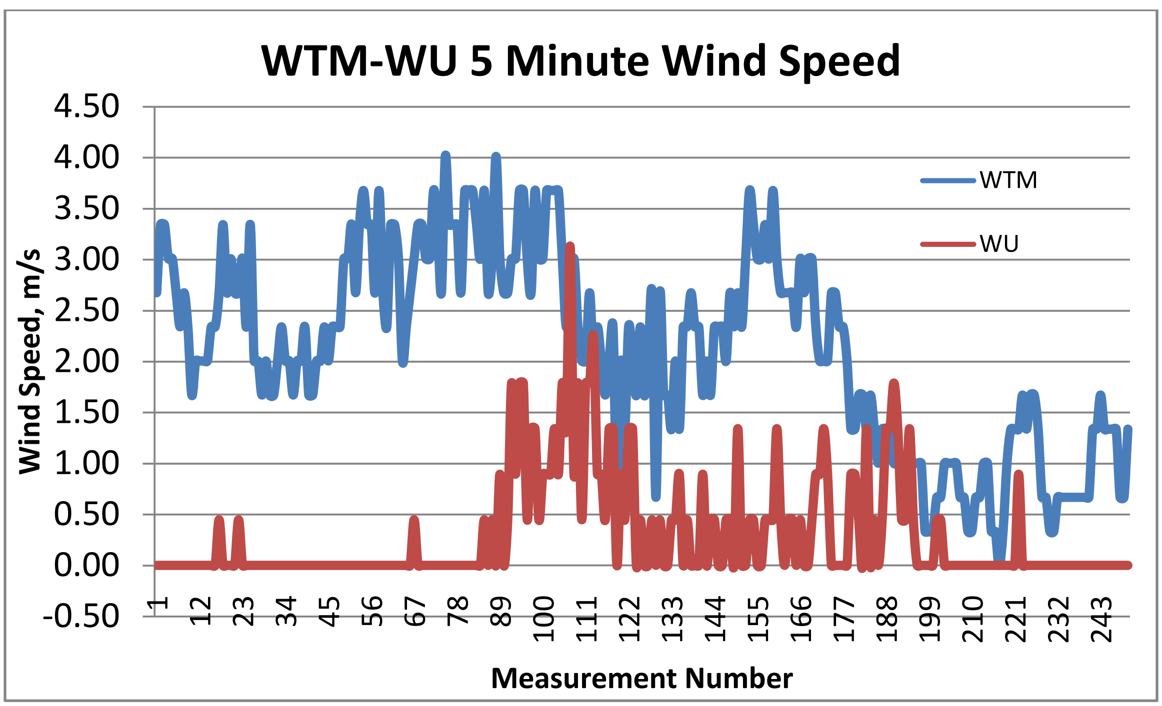


Figure D-34. Plot of Lubbock 5 minute data for wind speed.

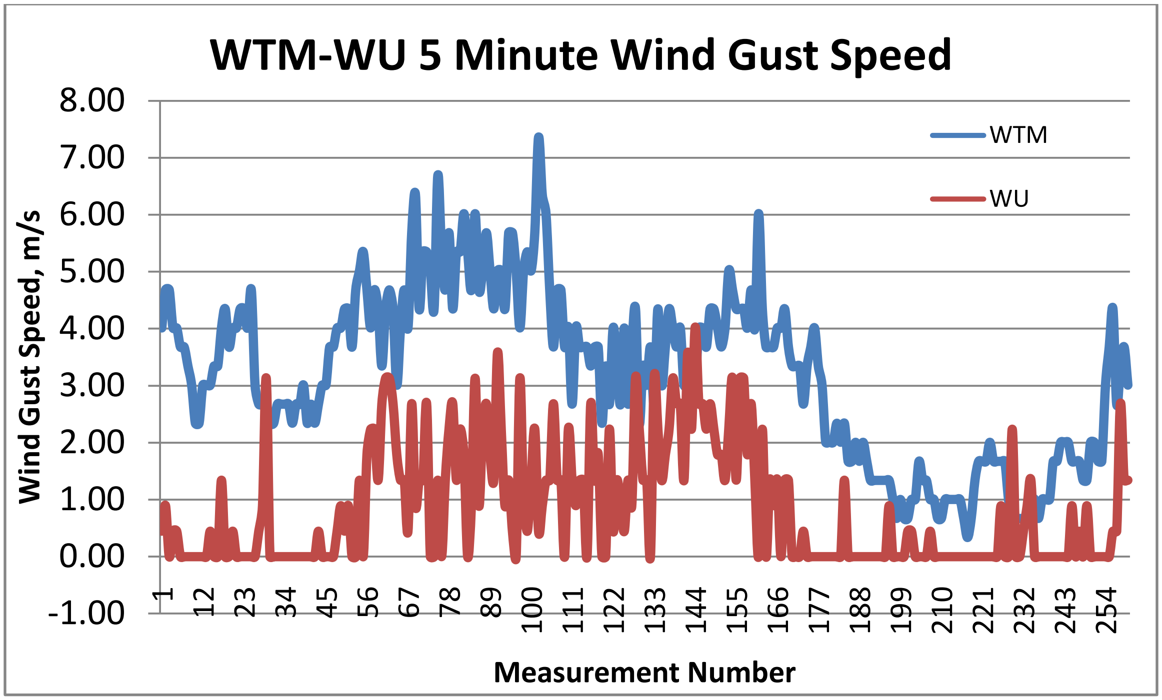


Figure D-35. Plot of Lubbock 5 minute data for wind gust speed.

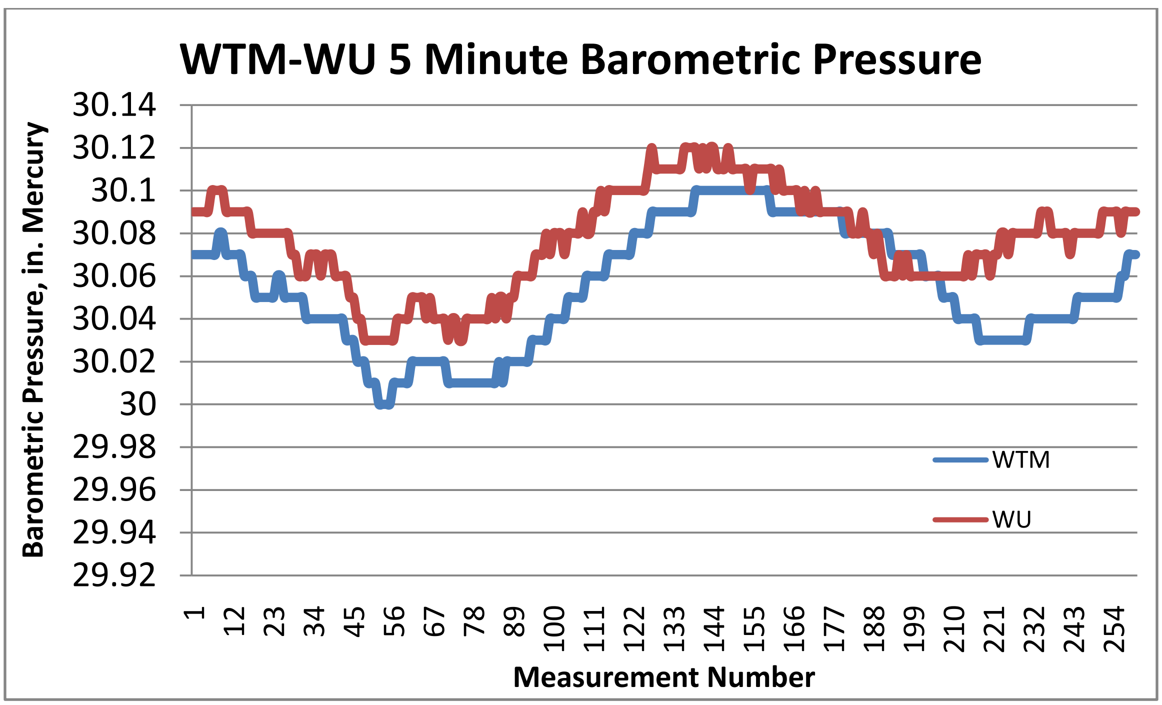


Figure D-36. Plot of Lubbock 5 minute data for barometric pressure.

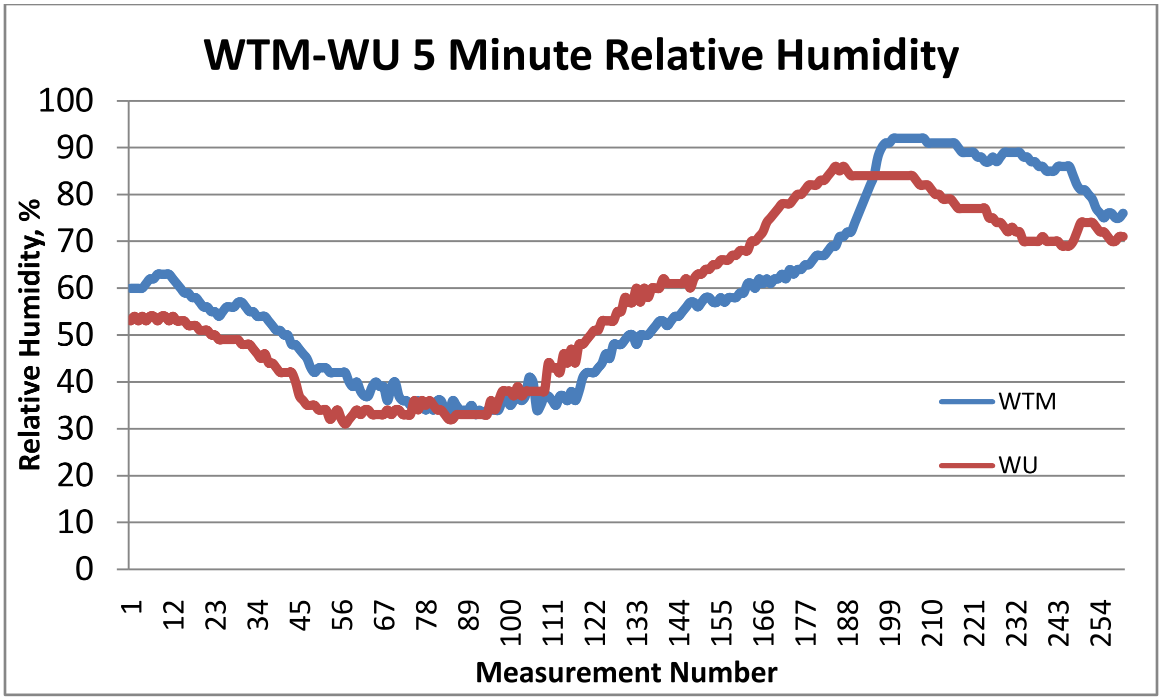
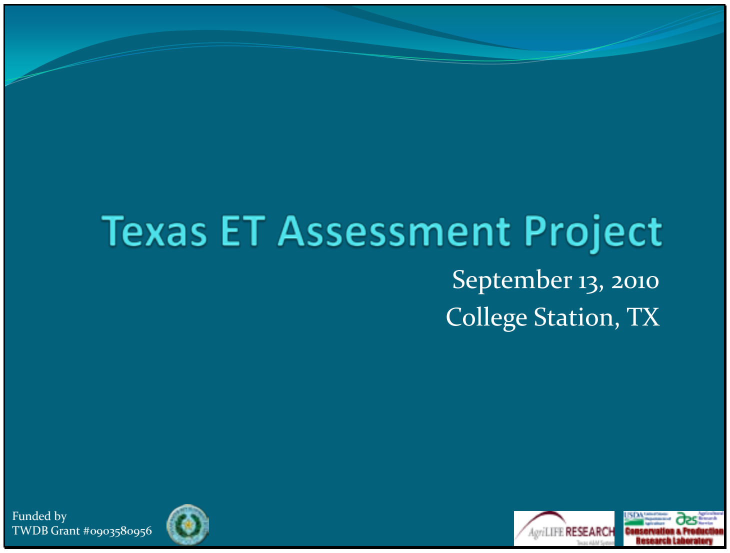


Figure D-37. Plot of Lubbock 5 minute data for relative humidity.

Appendix E- Slide Set of last workshop held in College Station in September 2010.

Slide 1



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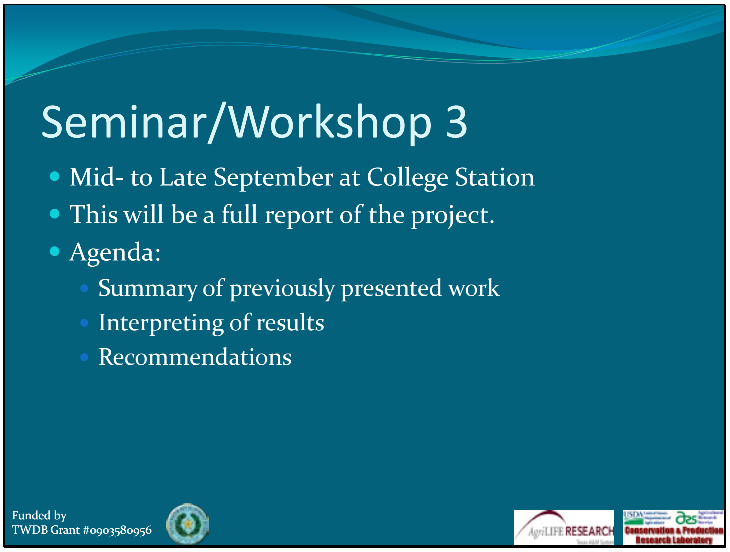
Slide 3



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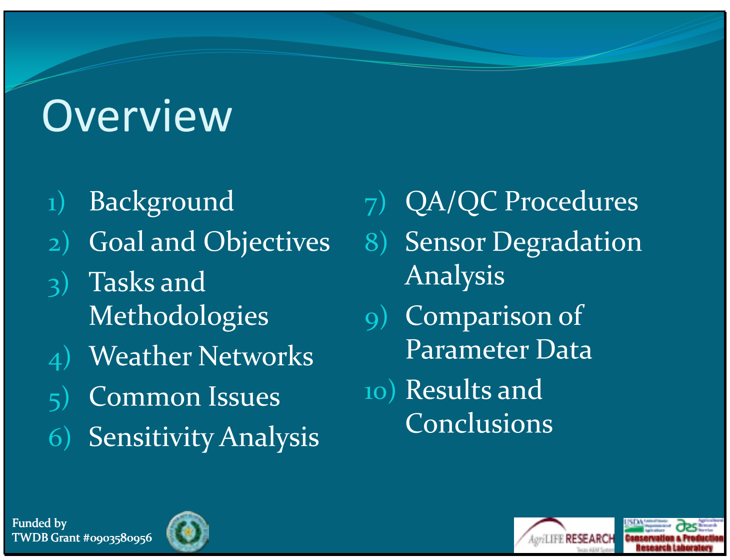

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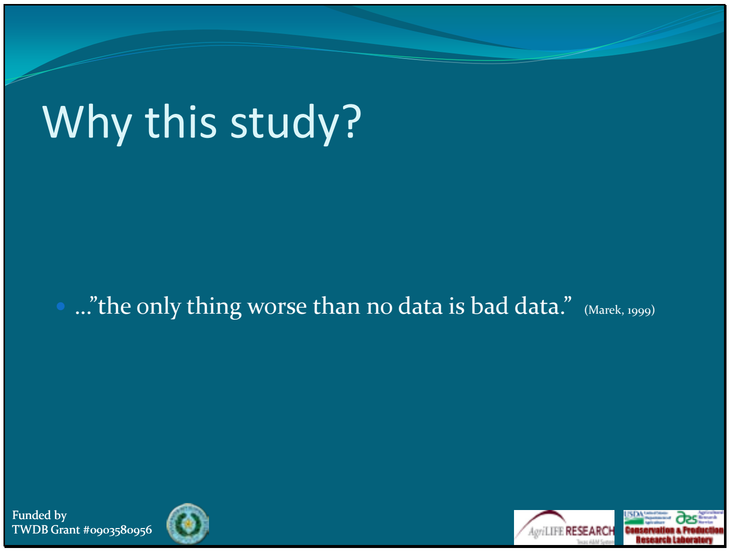

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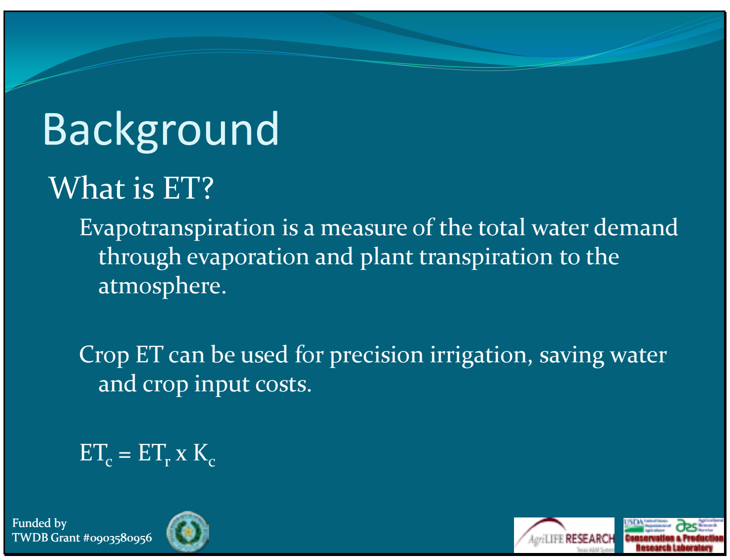

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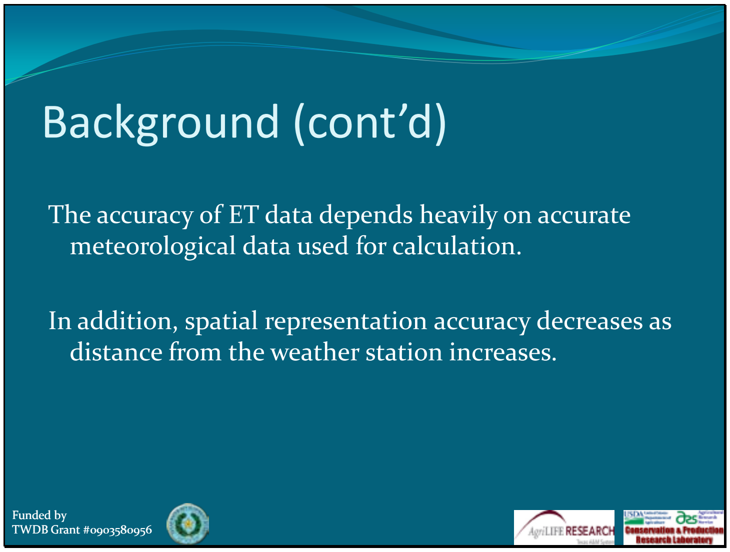

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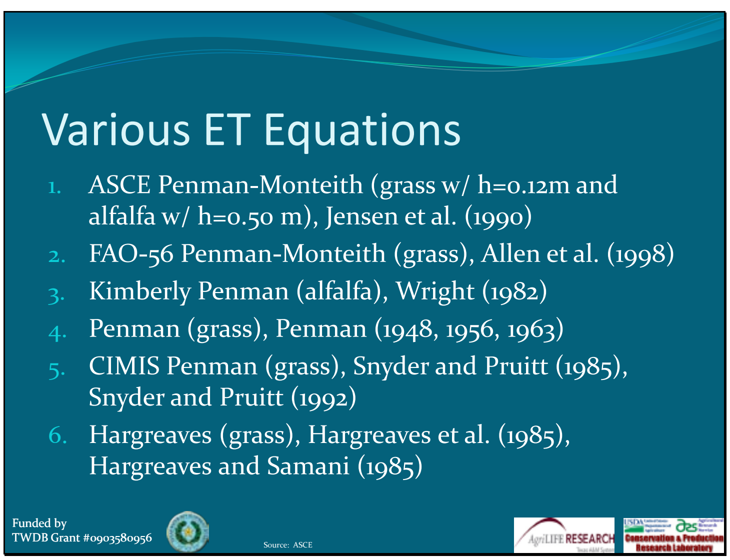

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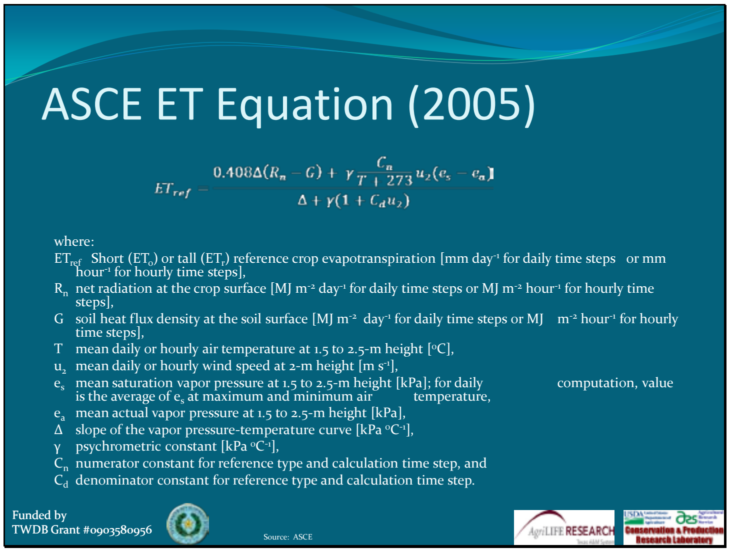

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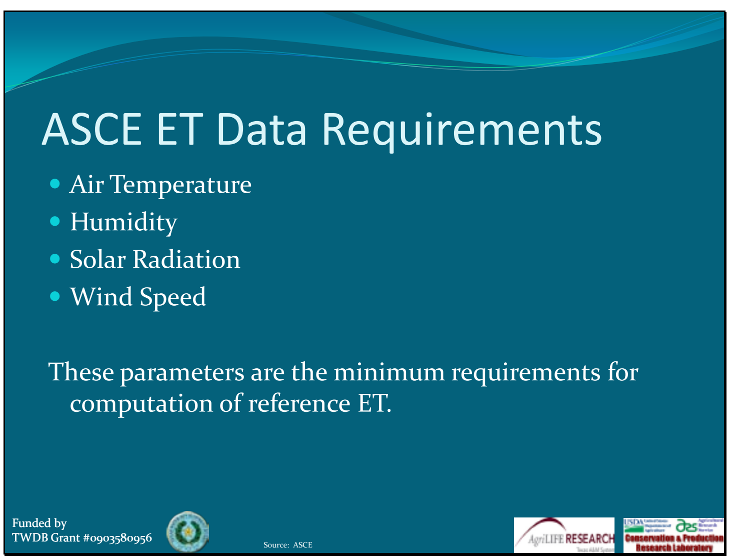

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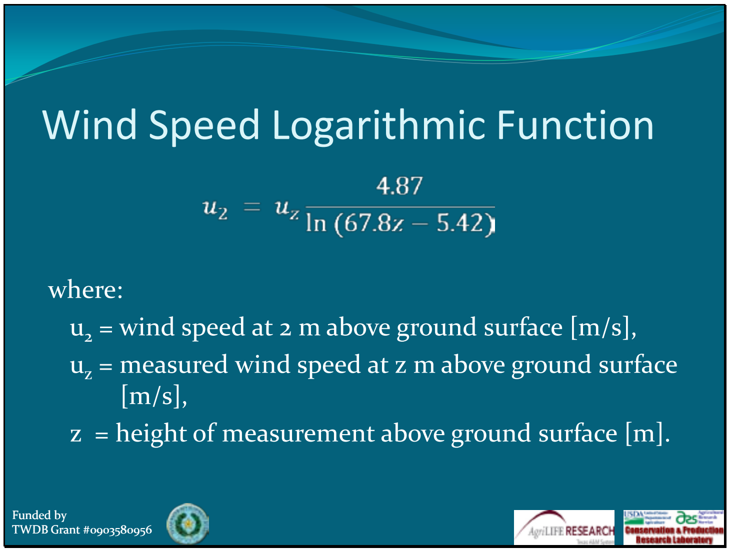

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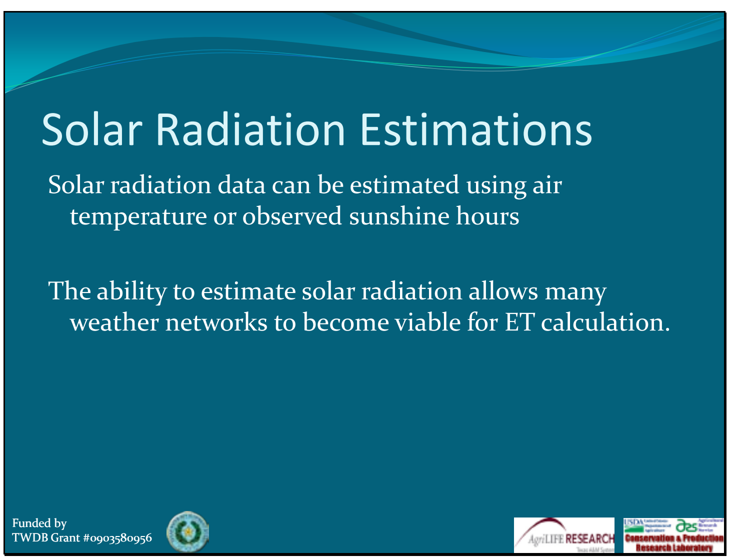

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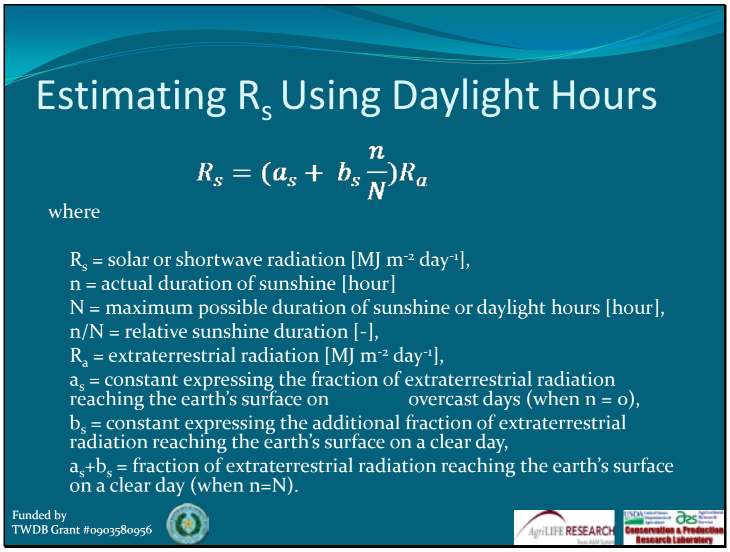

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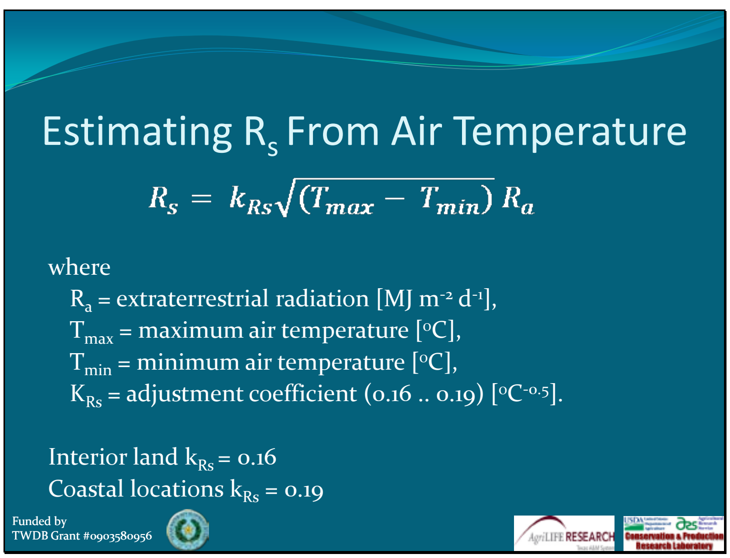

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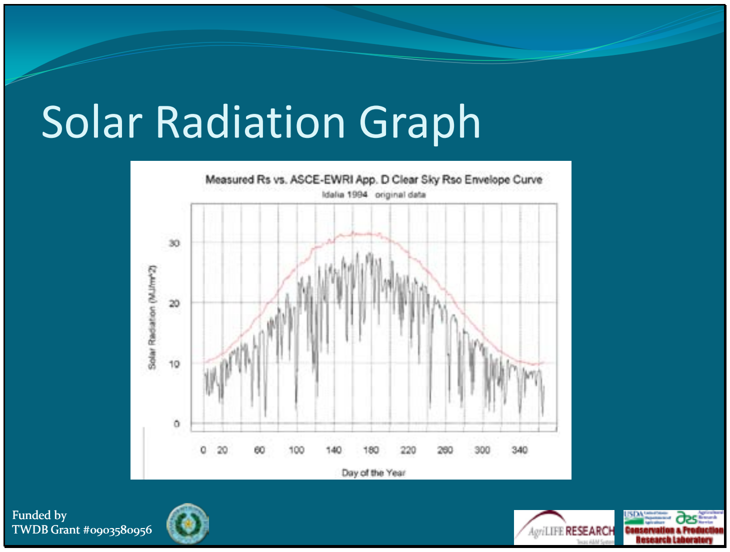

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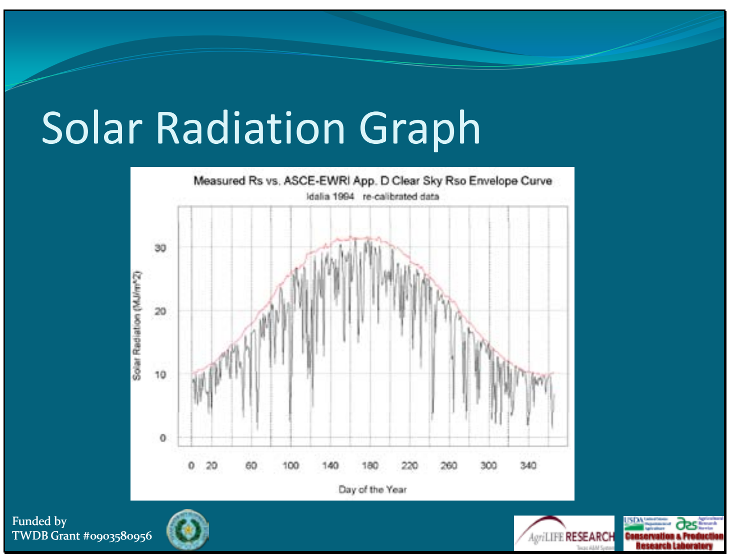

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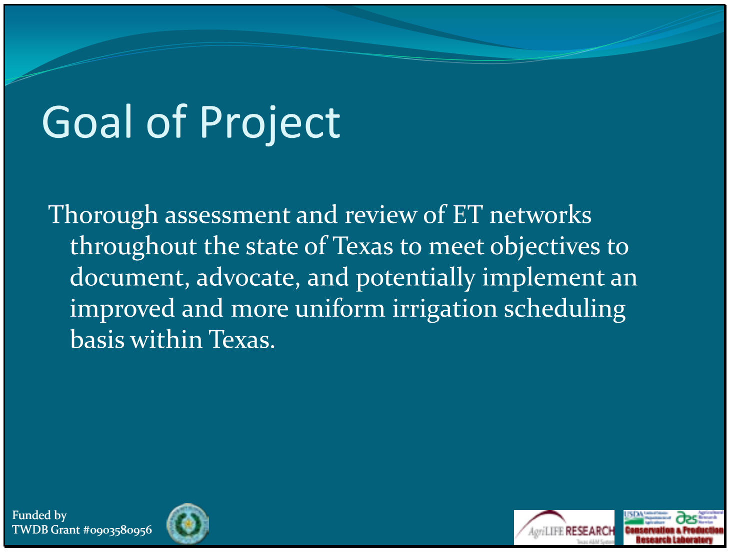

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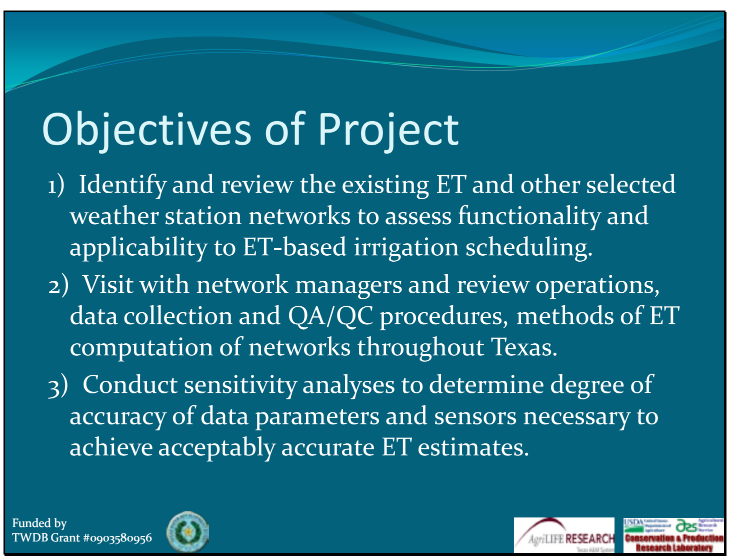


Slide 19

Objectives (cont’d)

4) Analyze commercially available weather station sensor degradation database(s) to determine the effects of sensor degradation (over time) on quality of data recorded by ET networks.

5) Compile and compare parameter data of existing ET networks and assess their suitability for irrigation scheduling applications.

6) Communicate results and provide recommendations regarding identified areas, instrumentation and methods of computation.

Funded by
TWDB Grant #0903580956

Slide 20

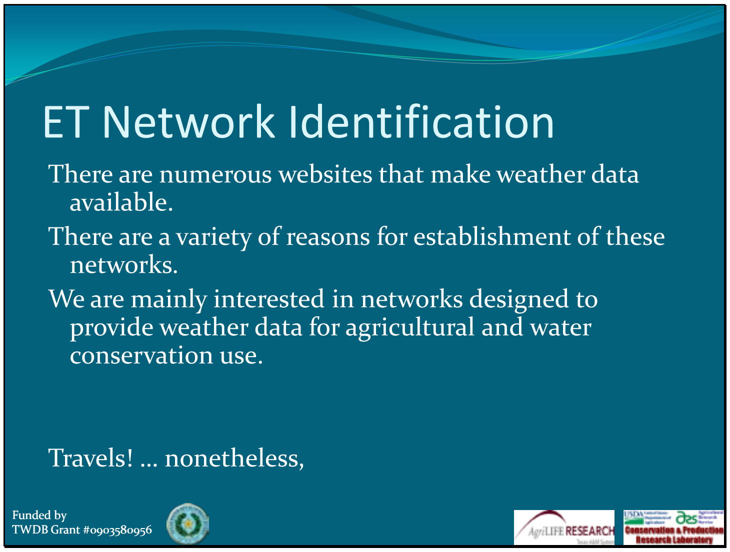
Thomas Marek

Task 1

- ET network identification

Funded by
TWDB Grant #0903580956

Slide 21



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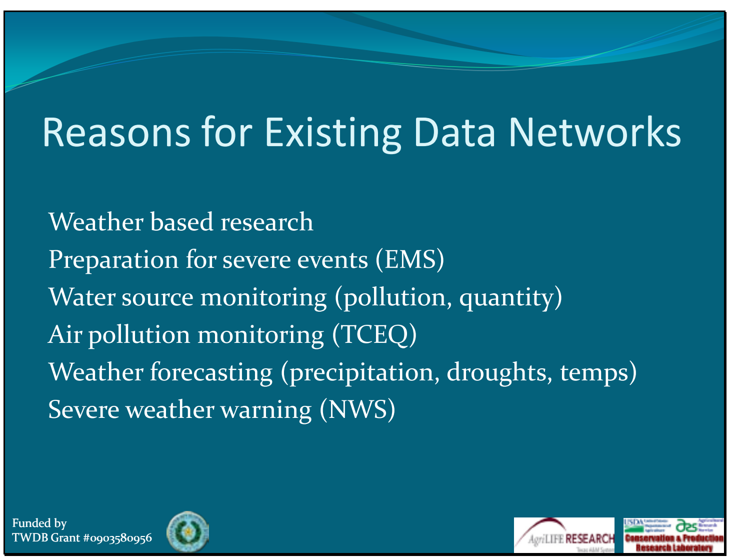

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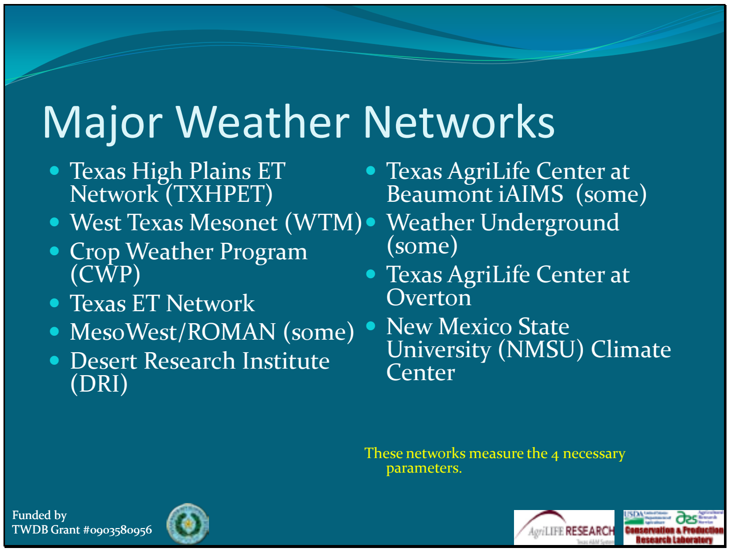

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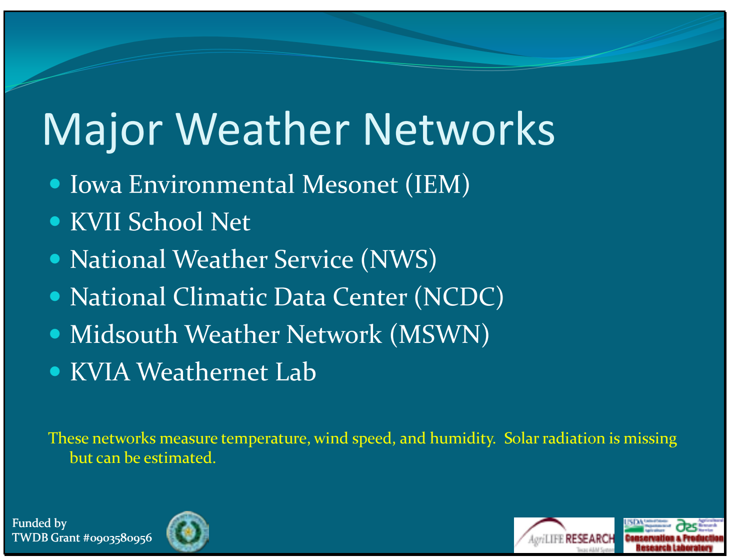

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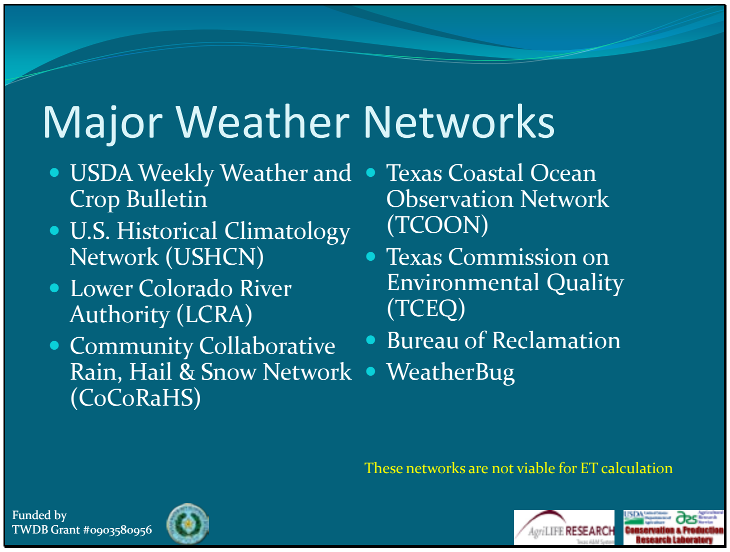

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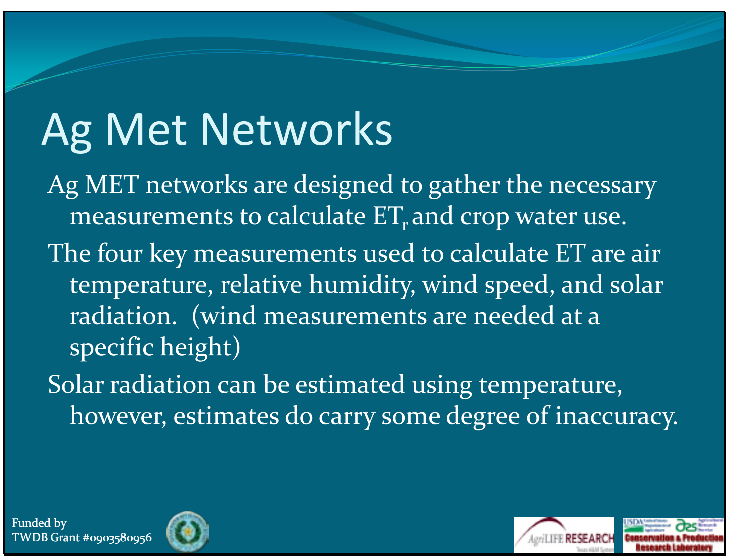

Slide 27

Ag Met Networks (cont'd)

Many agricultural networks measure more weather parameters than are needed for ET calculation.

Some networks measure soil moisture and soil temperature to assist in agricultural needs such as planting and harvesting.

The data and DSS tools also need to be readily available to growers and researchers for maximum benefit.

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TWDB Grant #0903580956

Slide 28

Other Networks

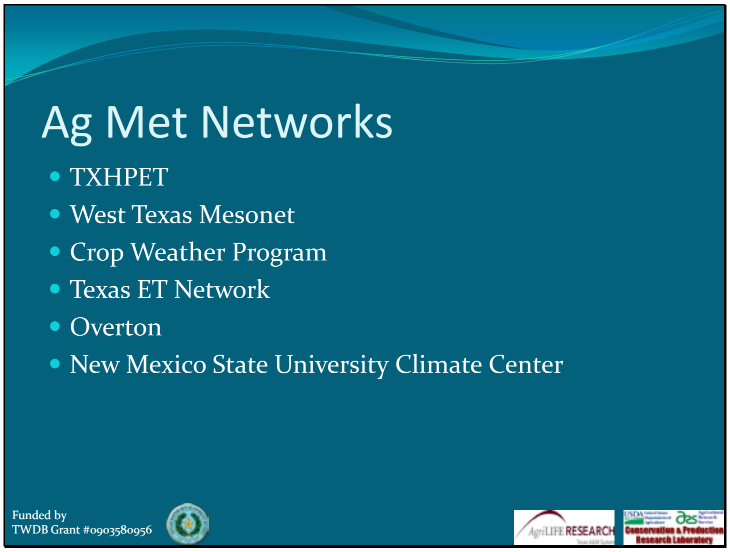
Networks with objectives that are not related to agriculture <u>may not</u> be suitable for use in irrigation scheduling. Validation can be a problem.

The necessary correlation parameters are often not measured for use in agricultural applications.

There are some cases where networks not designed for agricultural use contain necessary data and accuracy for ET calculation (with validation matrices).

Funded by
TWDB Grant #0903580956

Slide 29



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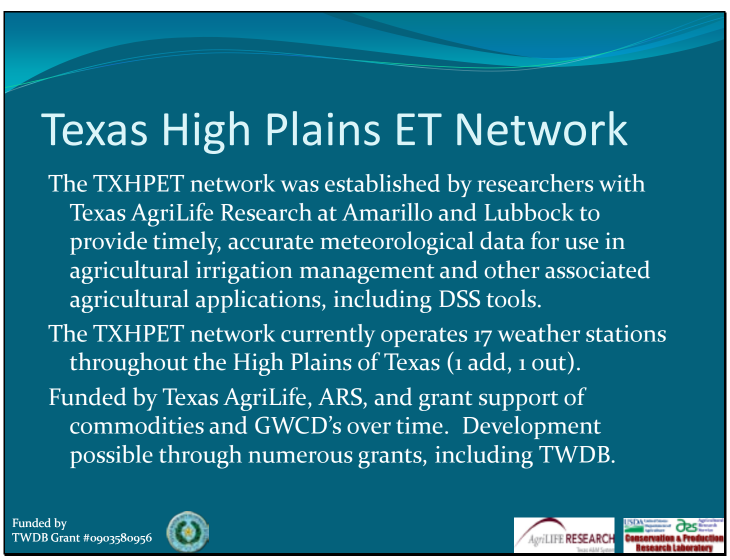

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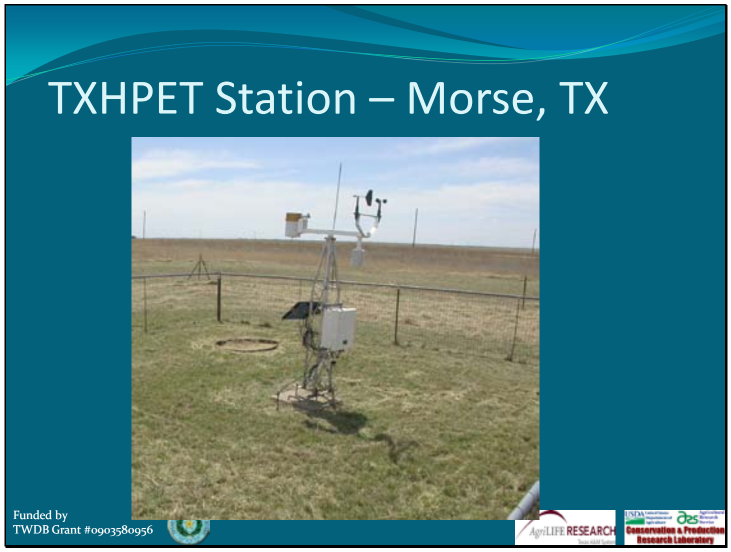

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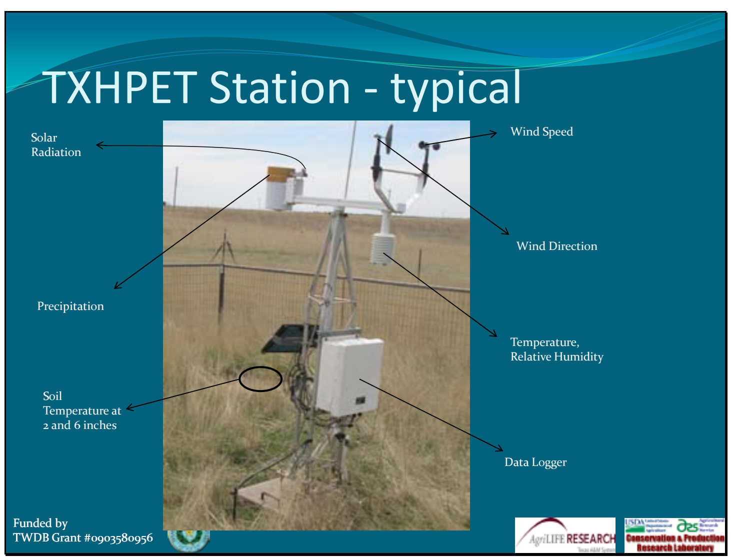

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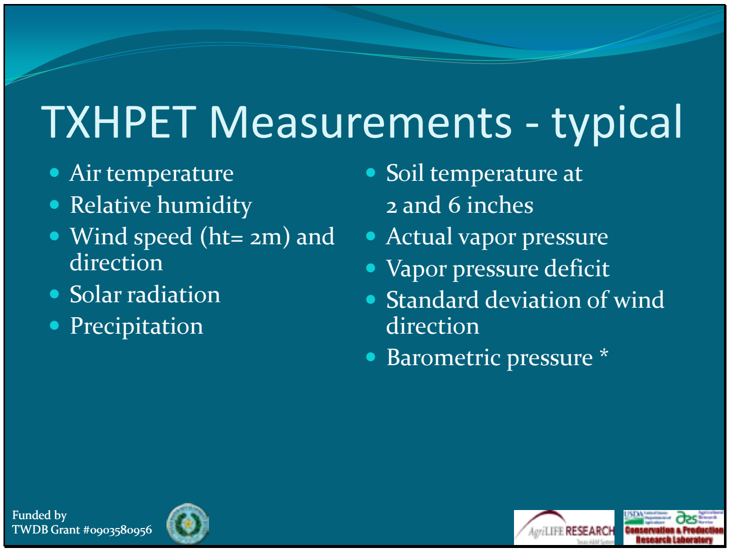

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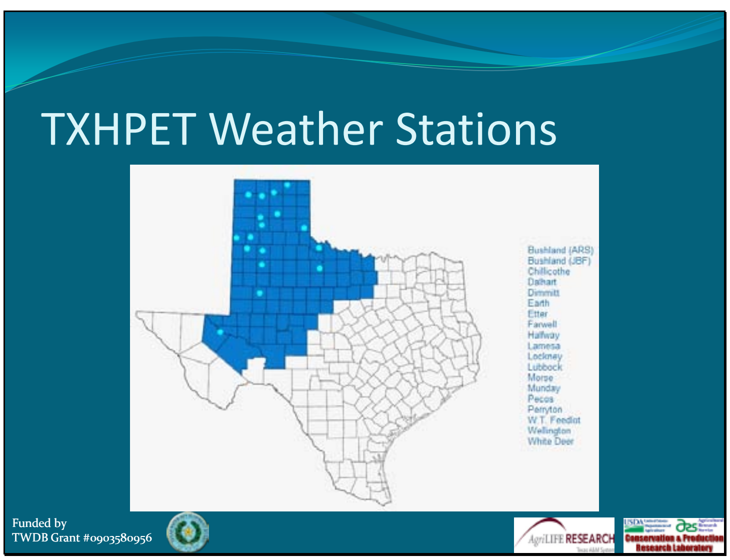


Slide 35

West Texas Mesonet

West Texas Mesonet was established by researchers at Texas Tech University in Lubbock. The purpose of this network is the provide free real-time weather and agricultural information for residents of the South Plains region of western Texas.

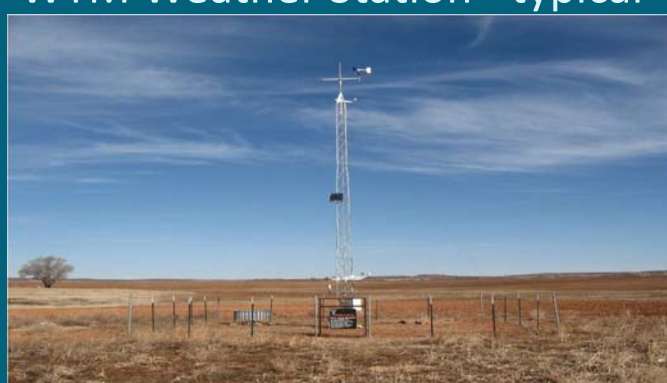
This network operates 55 weather stations throughout the South Plains of Texas.

Funding provided through Texas Tech University

Funded by
TWDB Grant #0903580956

Slide 36

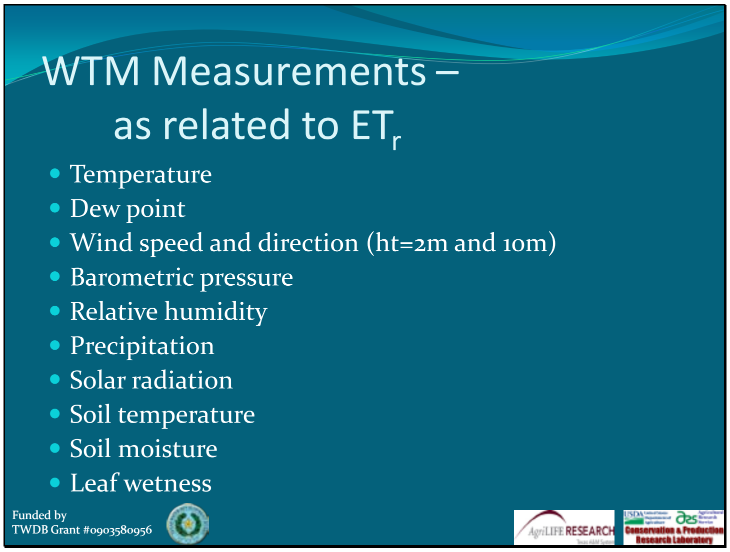
WTM Weather Station - typical



Funded by
TWDB Grant #0903580956

Source: WTM

Slide 37



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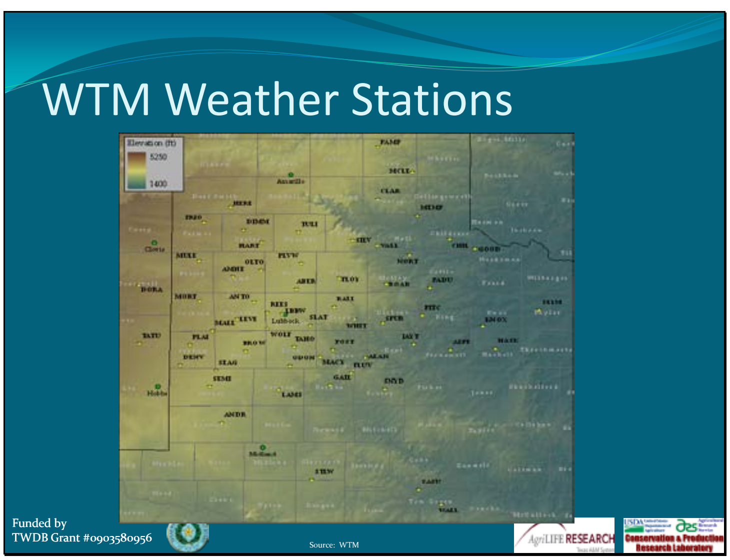
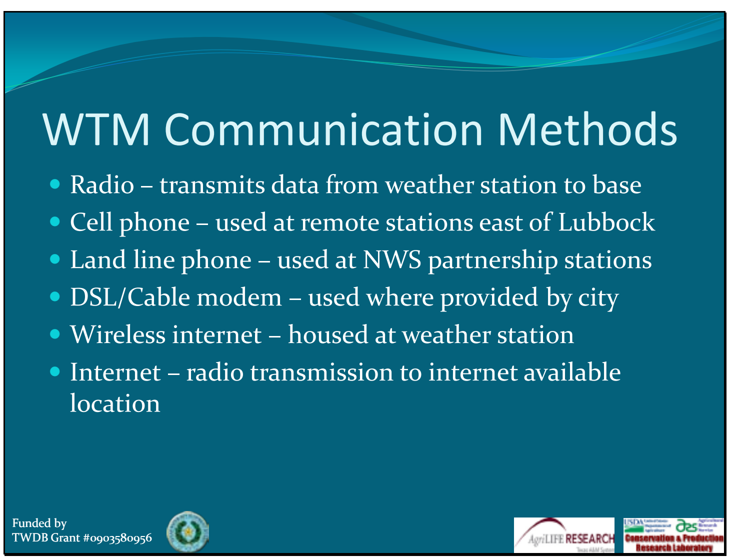


Slide 39

Slide 40



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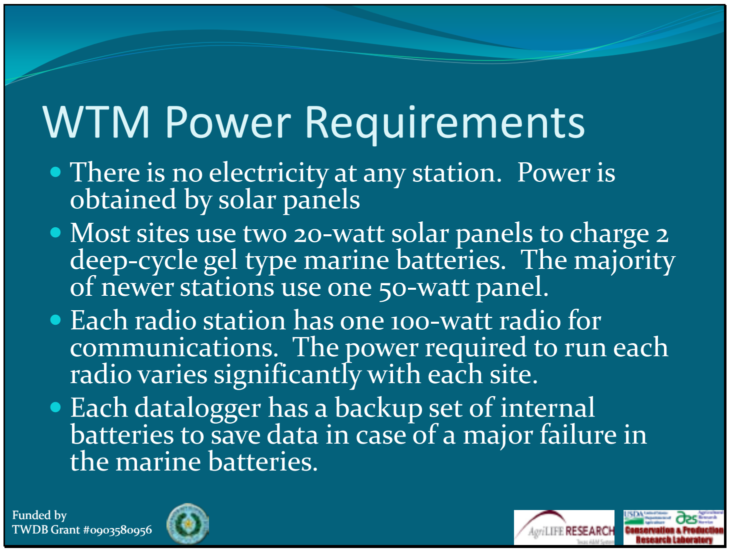

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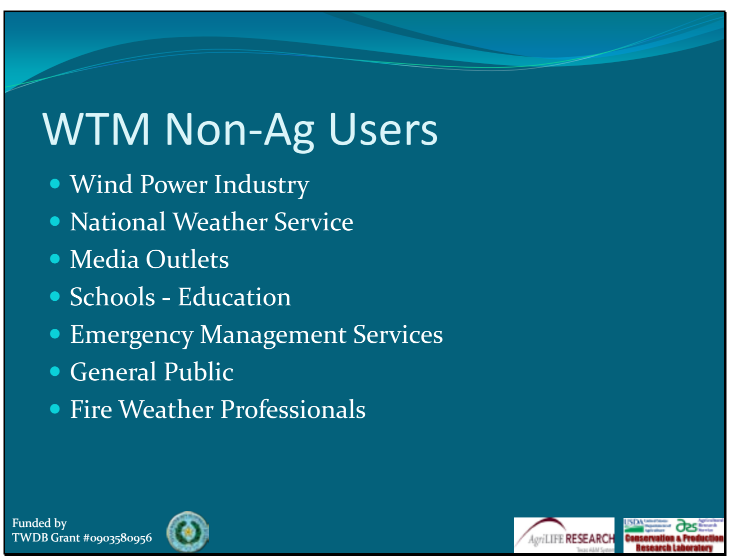

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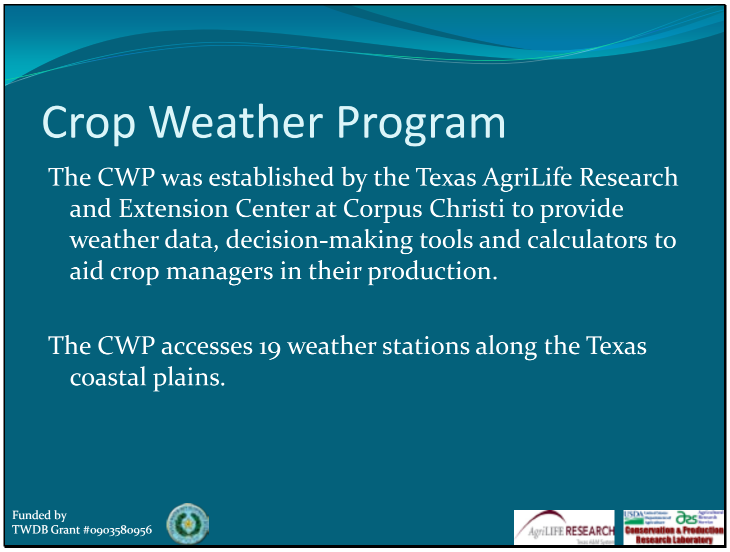

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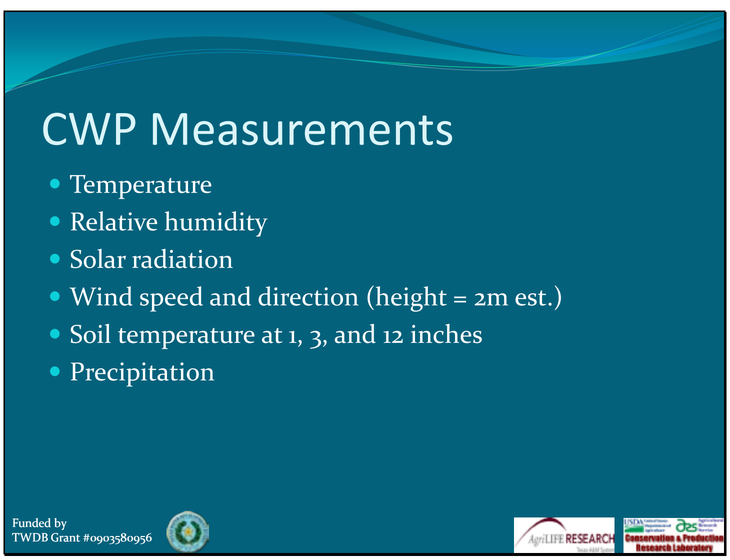

Slide 45

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Slide 47

CWP Station - typical

Funded by
TWDB Grant #0903580956

Source: CWP

Slide 48

Texas ET Network

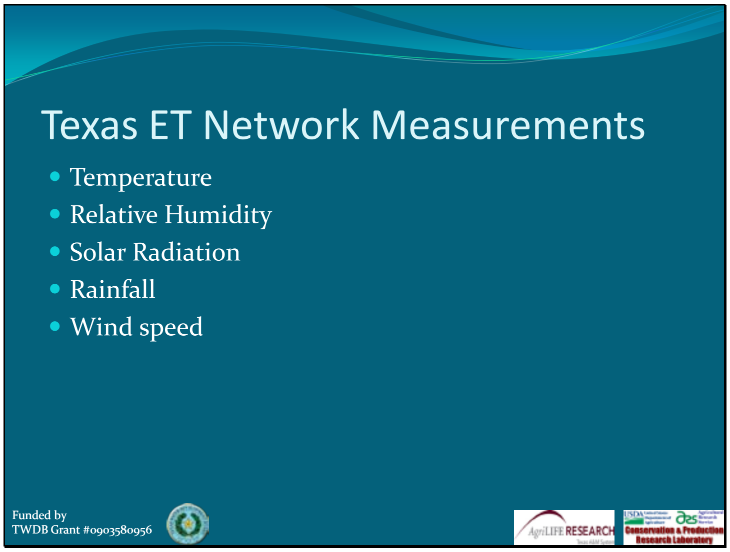
The Texas ET Network was established by Texas AgriLife Extension in College Station to provide weather and ET data to growers to assist in more efficient irrigation.

The Texas ET Network operates 28 weather stations throughout Texas.

Obtain k_c's form TXHPET research and FAO-56

Funded by
TWDB Grant #0903580956

Slide 49



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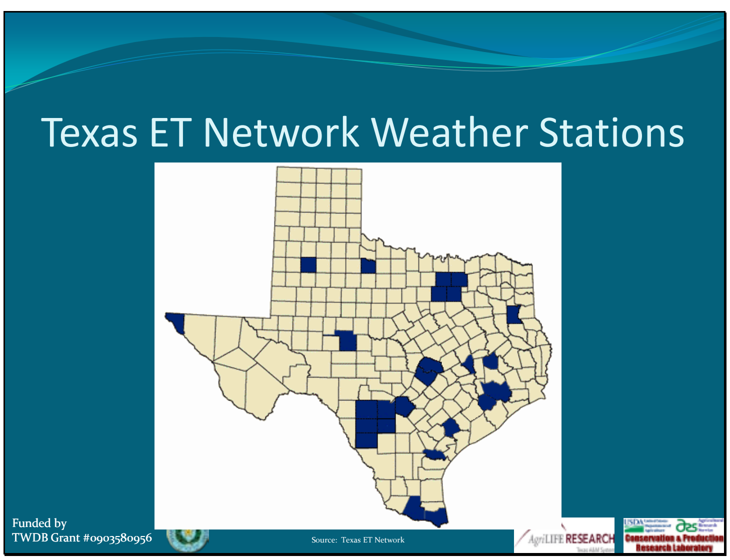

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Texas ET Network Weather Stations

Funded by
TWDB Grant #0903580956

Source: Texas ET Network

Slide 52

Texas AgriLife Center at Overton

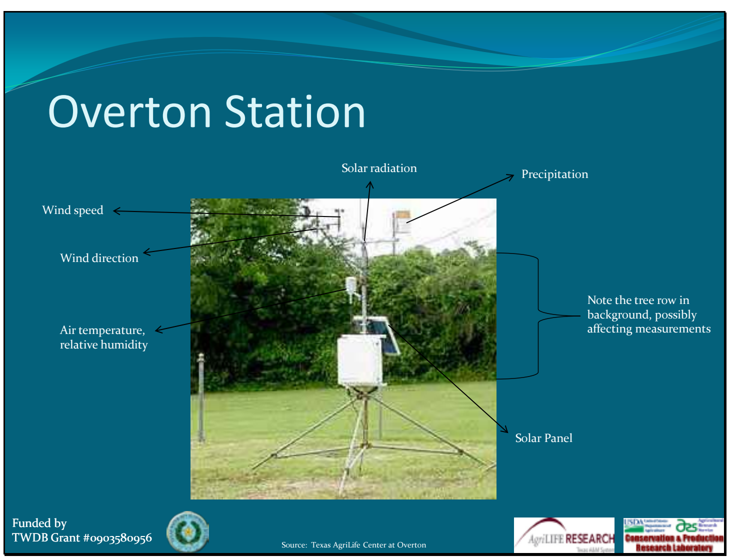
The Texas AgriLife Center at Overton created a website in 2004 to provide weather and potential evapotranspiration data to all interested parties, specific to the Sabine River Basin and greater northeast Texas.

The Overton Center operates only one weather station.

Funded by
TWDB Grant #0903580956

Slide 53

Slide 54



Slide 55

Overton Measurements

- Temperature
- Relative humidity
- Solar radiation
- Rainfall

Wind measurements are taken at an estimated 2m, but not available via the website.

This station is also monitored by the Texas ET Network.

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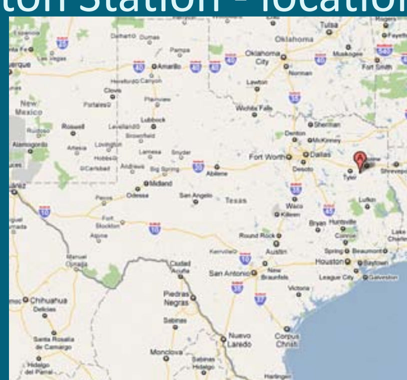
TWDB Grant #0903580956

Slide 56

Overton Station - location



Source: Texas AgriLife Center at Overton

Funded by
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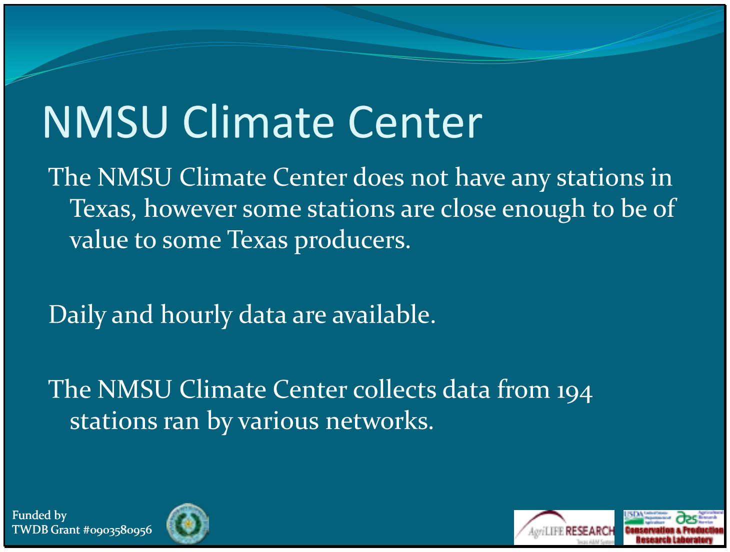
Slide 57



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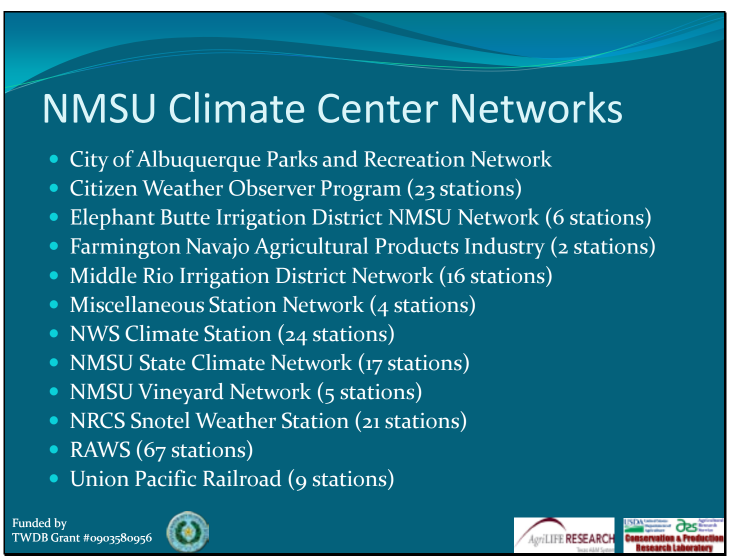


Slide 59

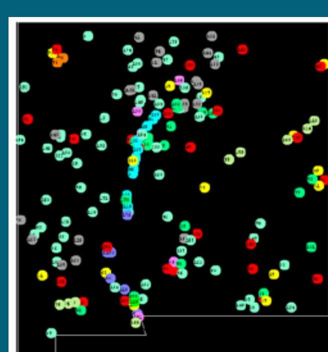
NMSU Measurements

- Temperature
- Humidity
- Precipitation
- Wind speed
- Wind direction
- Solar radiation
- Soil temperature

Funded by
TWDB Grant #0903580956

Slide 60

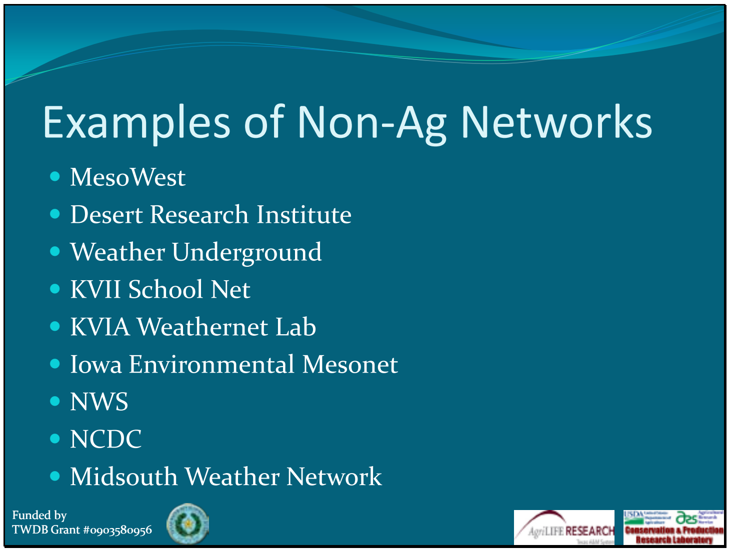
NMSU Stations



Source: NMSU Climate Center

Funded by
TWDB Grant #0903580956

Slide 61



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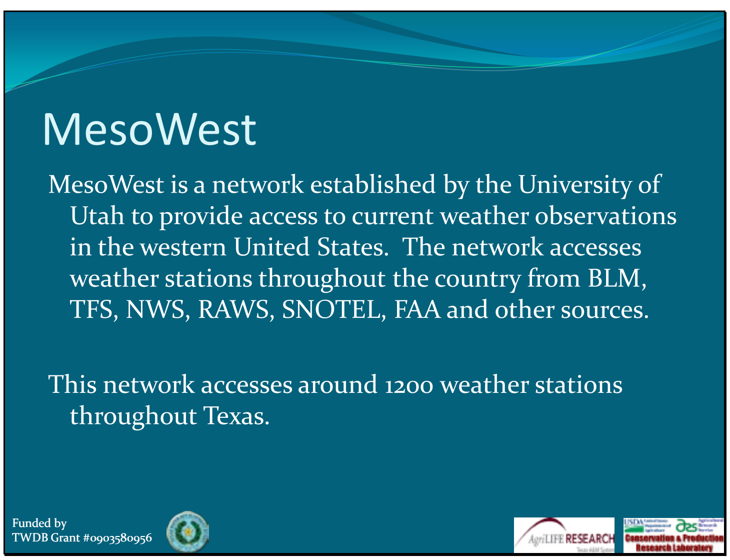


Slide 63

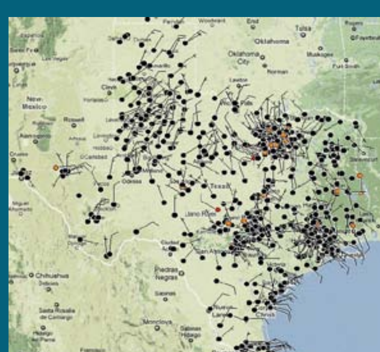
MesoWest Measurements

- Temperature
- Dew point
- Wet bulb temperature
- Relative humidity
- Wind speed and direction (ht varies)
- Atmospheric pressure
- Sea level pressure
- Solar radiation
- Precipitation

Funded by
TWDB Grant #0903580956

Slide 64

MesoWest Weather Stations



Source: MesoWest

Funded by
TWDB Grant #0903580956

Slide 65

Desert Research Institute (DRI)

The Western Regional Climate Center (WRCC) is a division of the Desert Research Institute located in Reno, Nevada. The WRCC provides access to data from Remote Automated Weather Stations (RAWS) throughout Texas.

There are 71 RAWS stations within Texas.

Funded by
TWDB Grant #0903580956

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RAWS

RAWS stations are located throughout the country and are used by a variety of governmental agencies to monitor air quality, rating fire danger, and providing information for research applications.

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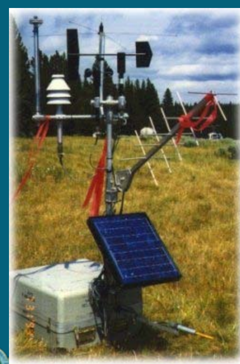
TWDB Grant #0903580956

Slide 67

RAWS Station - typical



Source: RAWS

Funded by
TWDB Grant #0903580956

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RAWS Partner Agencies

- US Department of Indian Affairs
- National Association of State Foresters
- Bureau of Land Management
- US Forest Service
- US Fish and Wildlife Service
- National Park Service

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TWDB Grant #0903580956

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RAWS Measurements

- Wind speed and direction (ht = 20ft)
- Precipitation
- Barometric Pressure
- Fuel moisture and temperature
- Air temperature
- Relative humidity

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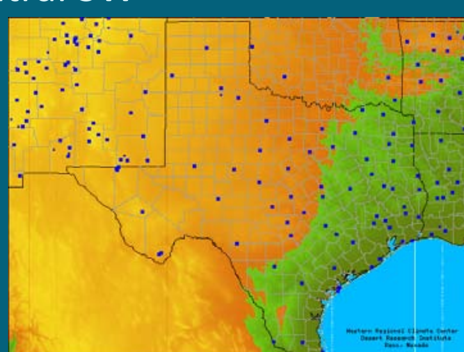
Slide 70

RAWS Weather Stations – central SW



Funded by
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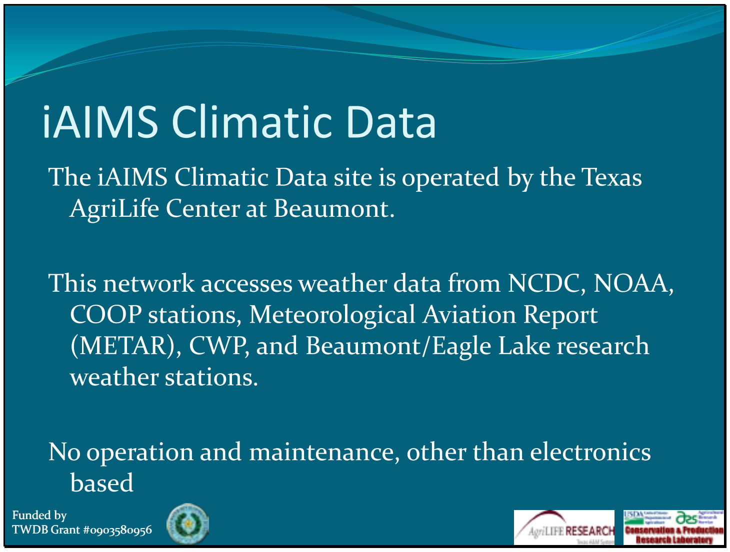

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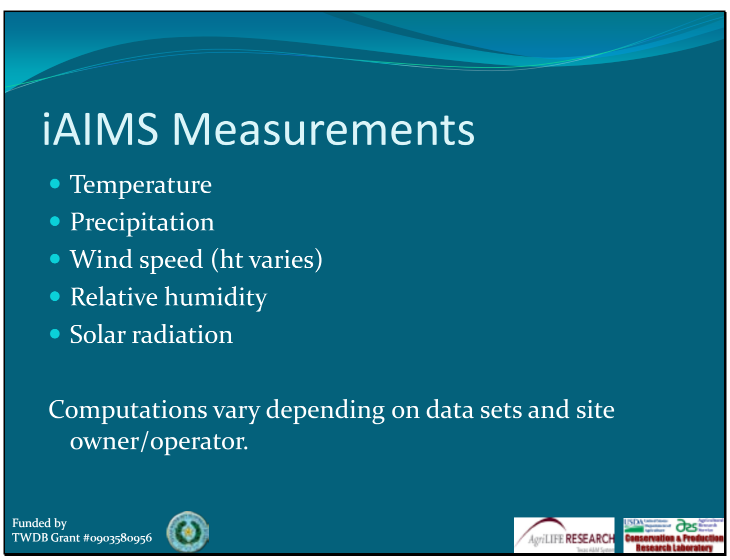

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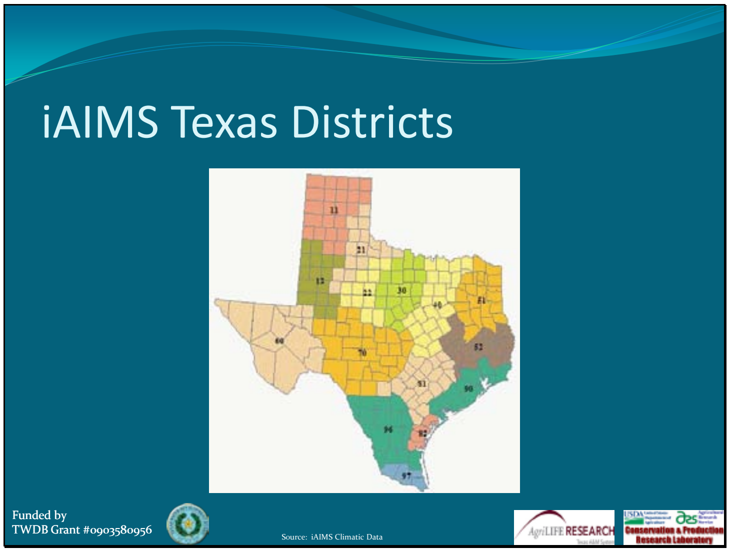

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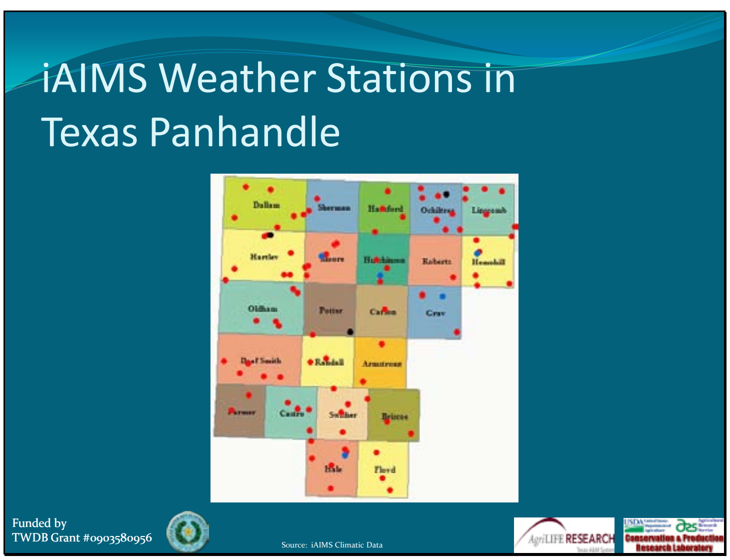

Slide 75

Weather Underground

Weather Underground is a website that was developed at the University of Michigan to provide reliable, accurate weather information.

This site accesses 1573 weather stations throughout Texas.

Some base on personal installations (no accuracy warranted or inferred)

QA/QC is an issue

Purely a clearing house with variation in types/accuracy

Funded by
TWDB Grant #0903580956

Slide 76

Weather Underground Measurements

- Temperature
- Dew point
- Barometric pressure
- Wind speed and direction (ht varies)
- Wind gust
- Humidity
- Rainfall rate
- Solar radiation (at some sites)

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TWDB Grant #0903580956

Slide 77

Weather Underground TX Panhandle Stations

Graphic does not show all stations monitored within area

Source: Weather Underground

Funded by
TWDB Grant #0903580956

AgriLIFE RESEARCH

USDA ARS Conservation & Production Research Laboratory

Slide 78

Iowa Environmental Mesonet

The Iowa Environmental Mesonet (IEM) was designed by researchers at Iowa State University to gather, collect, compare, disseminate and archive observations made in Iowa.

Although this network was not designed specifically for Texas, it does provide access to Automated Surface Observing System (ASOS) weather stations in Texas.

There are 170 stations located at airports to provide data for the NWS and FAA in **TEXAS**.

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TWDB Grant #0903580956

AgriLIFE RESEARCH

USDA ARS Conservation & Production Research Laboratory

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ASOS Weather Stations

ASOS stations are utilized by the NWS and FAA.

ASOS stations are located at most municipal airports throughout the country.

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Slide 80

ASOS Station

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TWDB Grant #0903580956

Source: NOAA

Slide 81

ASOS Measurements

- Air temperature
- Dew point
- Relative humidity
- Wind speed and direction (ht = 10m)*
- Solar radiation
- Air pressure
- Precipitation

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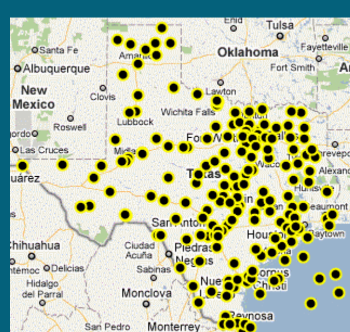
ASOS Weather Stations



Source: Iowa Environmental Mesonet

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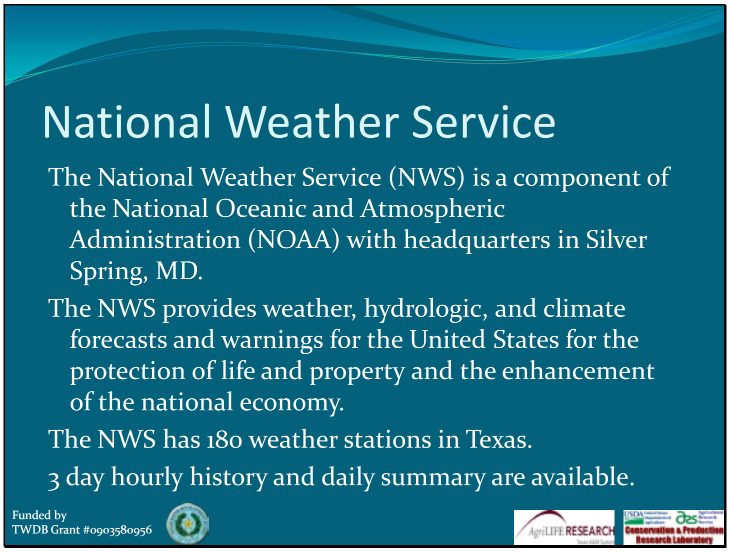

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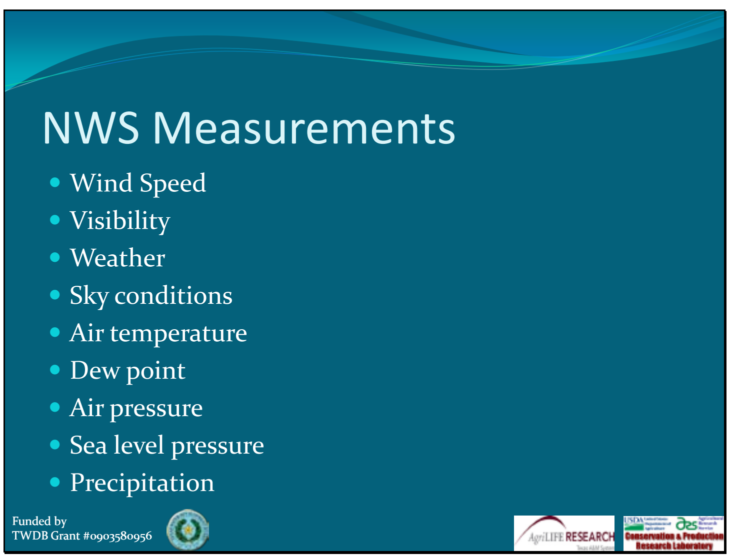

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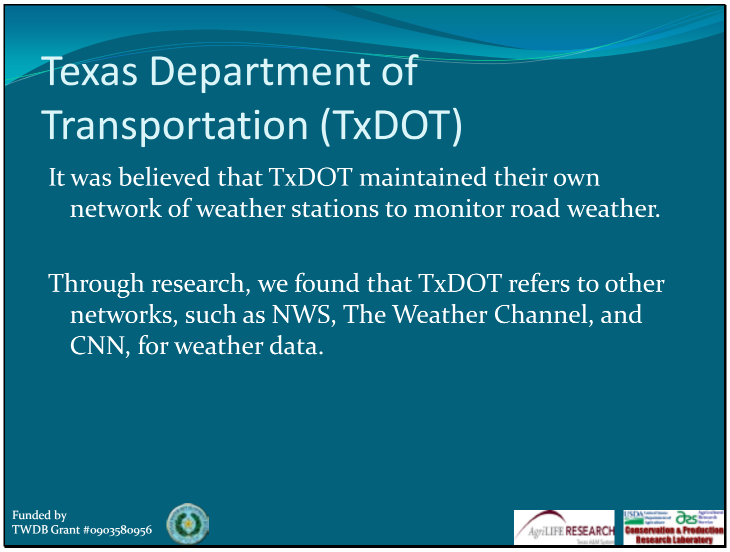

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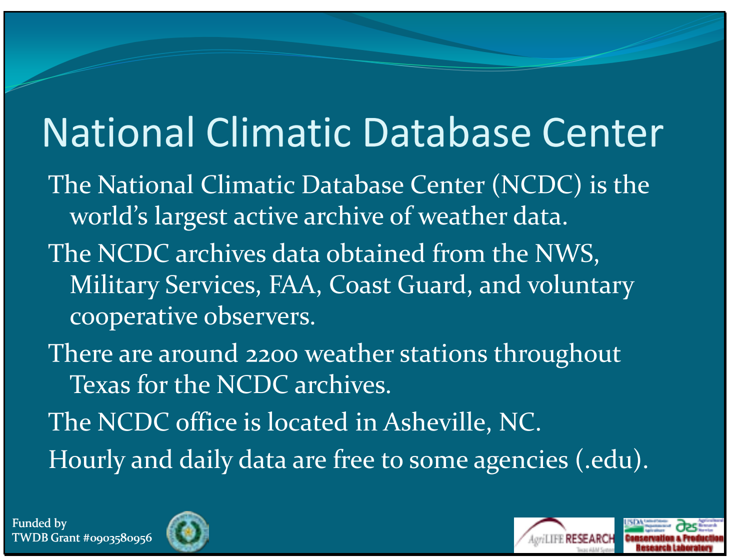

Slide 87

NCDC ASOS Station – Huntsville, TX

Funded by
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Source: NCDC

Slide 88

NCDC

- There are several products and services available from the NCDC.
- The most useful product for agriculture use is the global summary of the day (including 3 parameters, R_s missing).
- This displays daily data from a selected location or multiple locations

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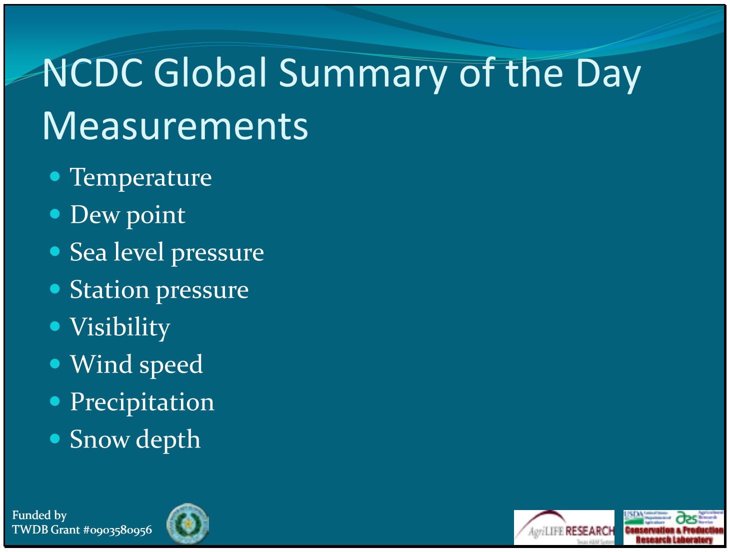

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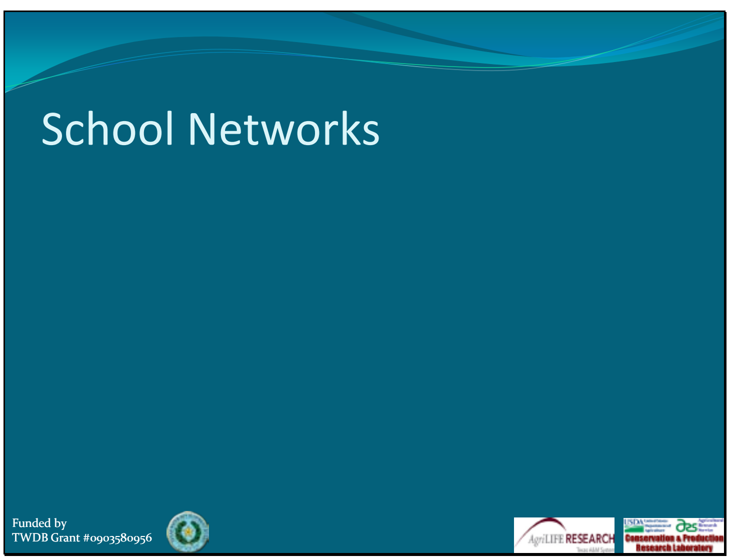

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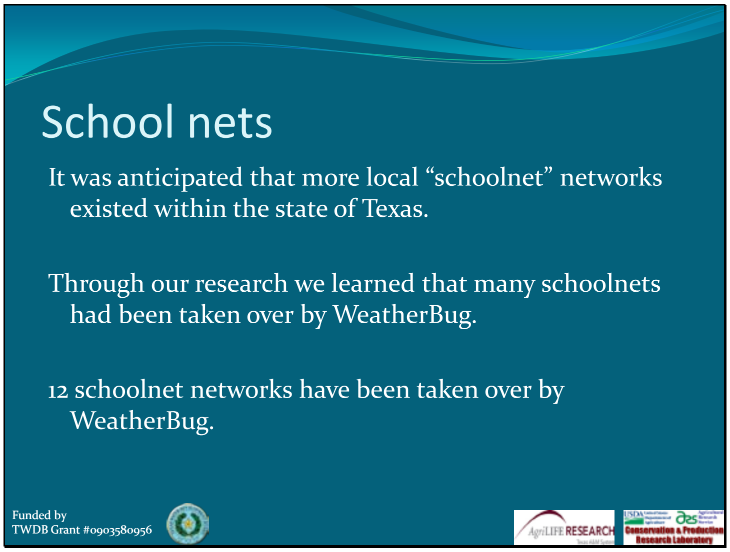

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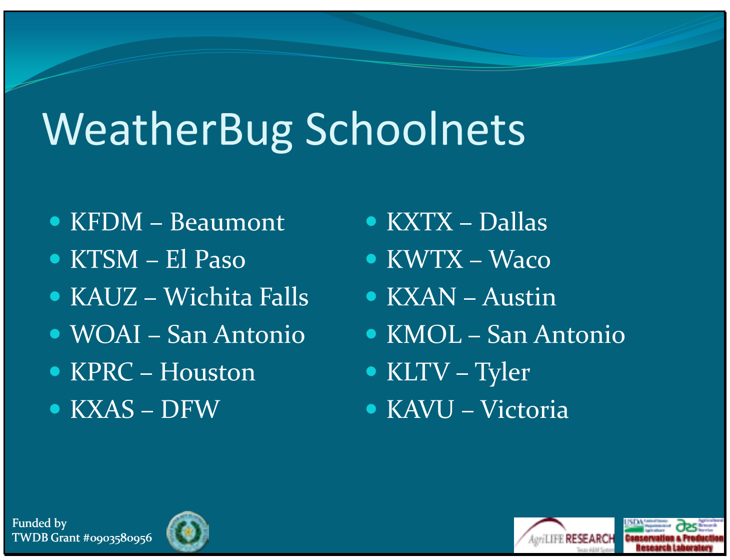

Slide 93

WeatherBug

The WeatherBug network was not designed for use in agricultural applications and does not make historical data available.

WeatherBug was developed with the purpose of delivering live local weather conditions, forecasts and life saving severe weather alerts from its exclusive network of WeatherBug Tracking Stations.

Funded by
TWDB Grant #0903580956

Slide 94

WeatherBug Stations in TX

This graphic does not show all WeatherBug stations.

Funded by
TWDB Grant #0903580956

Source: Weatherbug

Slide 95

WeatherBug Stations Around DFW

Funded by
TWDB Grant #0903580956

Source: Weatherbug

Slide 96

KVII School Net

An Amarillo TV station, KVII, created School Net.

It is a network of around 100 weather stations located throughout the Texas panhandle.

This network was created to give students a hands-on learning tool, give teachers a way to teach meteorology in an exciting way, and give viewers their town's weather data live.

Funded by
TWDB Grant #0903580956

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School Net Measurements

- Temperature
- Wind chill
- Dew point
- Heat index
- Wind speed and direction (ht varies)
- Pressure
- Humidity
- Rainfall

*These stations are generally located on top of buildings – not valuable for agricultural applications

Funded by
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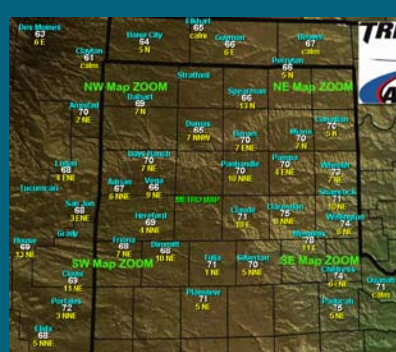
Slide 98

School Net Stations in Texas Panhandle



Funded by
TWDB Grant #0903580956

Source: KVII

Slide 99

KVIA – El Paso, TX
Weathernet Lab

An El Paso TV station, KVIA, created Weathernet Lab.

It is a network of 17 station around El Paso.

This network only displays current measurements and does not provide any historical data

Funded by
TWDB Grant #0903580956

Slide 100

Weathernet Lab Measurements

- Temperature
- Wind chill
- Dew point
- Heat index
- Wind speed and direction
- Pressure
- Humdiity
- Rainfall

Funded by
TWDB Grant #0903580956

Slide 101

Midsouth Weather Network

Midsouth Weather Network (MSWN) is a network of personal weather stations throughout Texas, Oklahoma, Arkansas, and Louisiana.

There are 12 stations in Texas.

Data from these stations are reported to Weather Underground and NOAA.

The network website links the different stations data websites to one map.

QA/QC is a potential issue.

Funded by
TWDB Grant #0903580956

Slide 102

MSWN Measurements

- Temperature
- Dew point
- Humidity
- Average wind speed and direction
- Wind gust speed
- Rain
- Barometric pressure
- Barometric pressure trend

Funded by
TWDB Grant #0903580956

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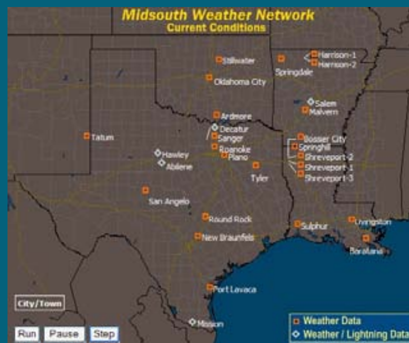
MSWN Stations



Funded by
TWDB Grant #0903580956

Source: MSWN

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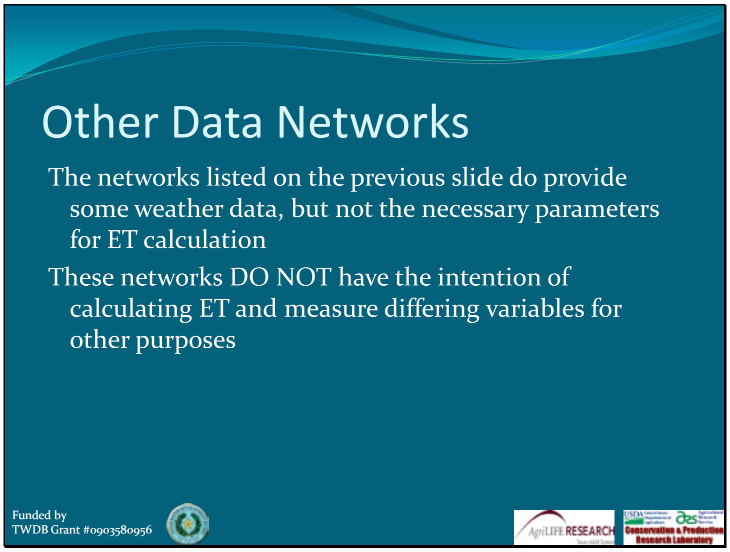
Other Data Networks

- USDA Weekly Weather and Crop Bulletin
- U.S. Historical Climatology Network (USHCN)
- Bureau of Reclamation
- Lower Colorado River Authority (LCRA)
- Community Collaborative Rain, Hail & Snow Network (CoCoRaHS)
- Texas Coastal Ocean Observation Network (TCOON)
- Texas Commission on Environmental Quality (TCEQ)

Funded by
TWDB Grant #0903580956

Slide 105



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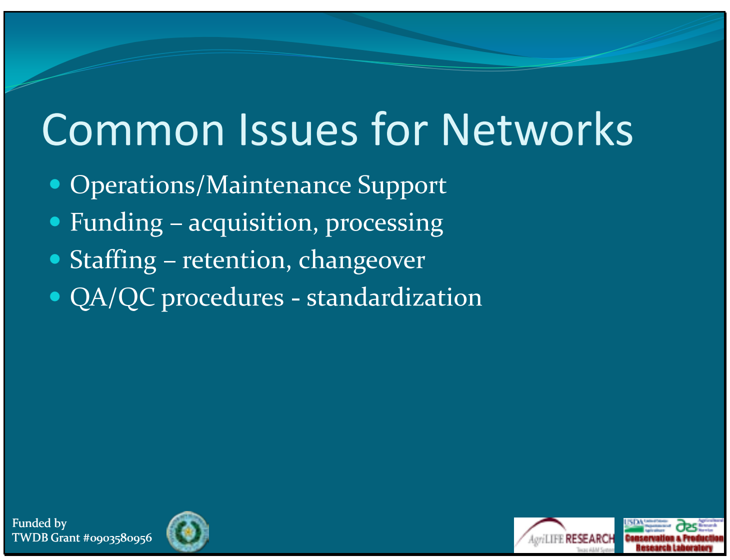

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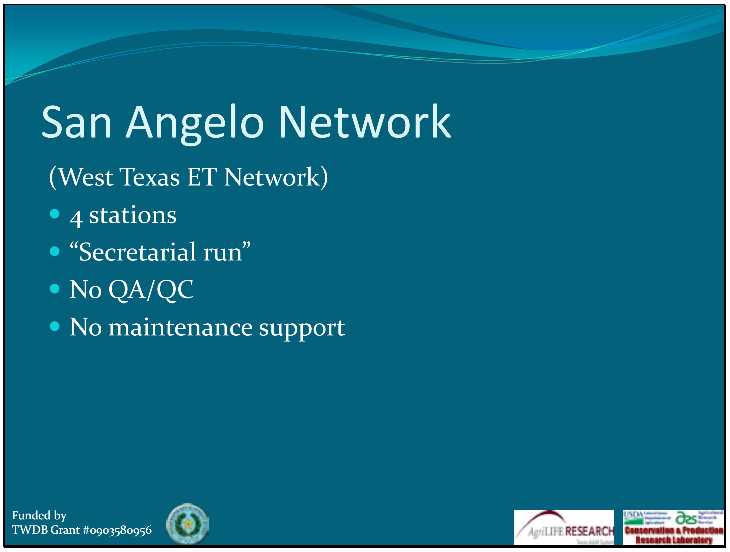

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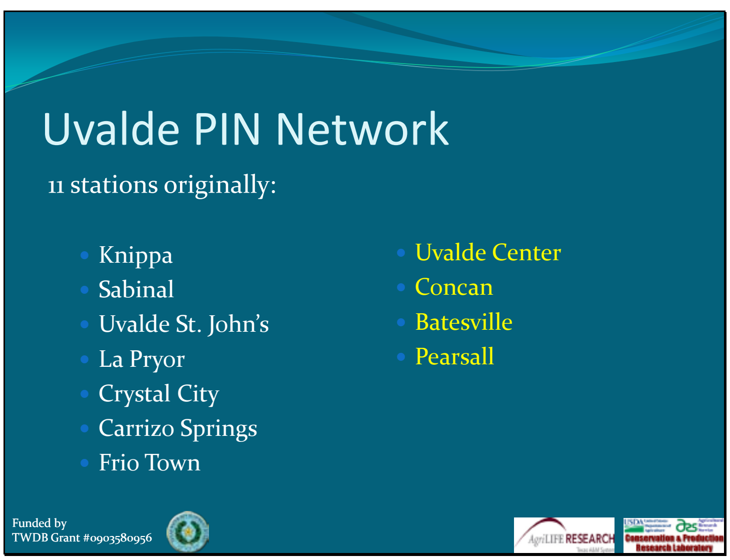

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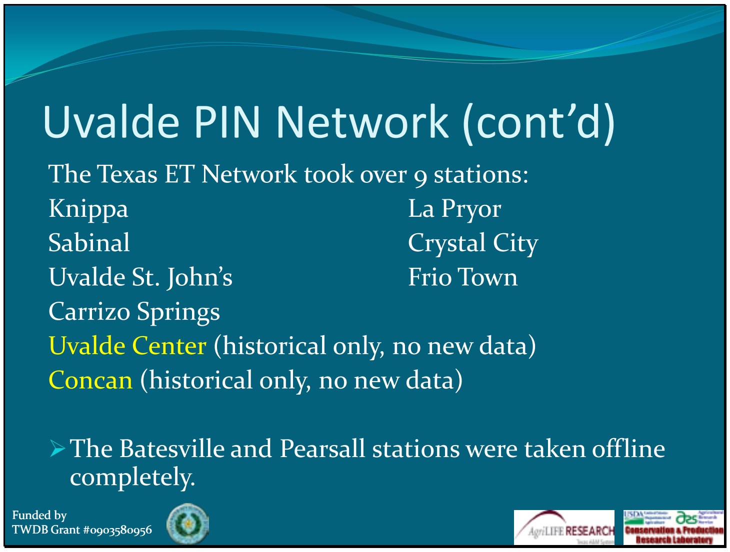

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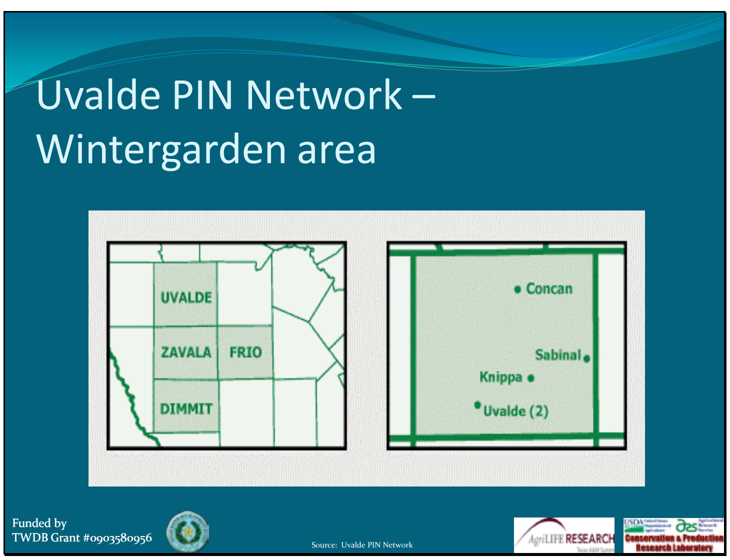

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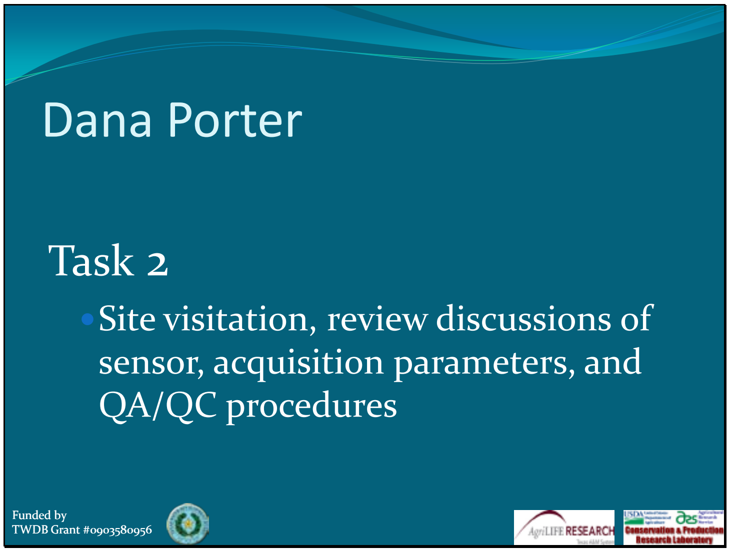

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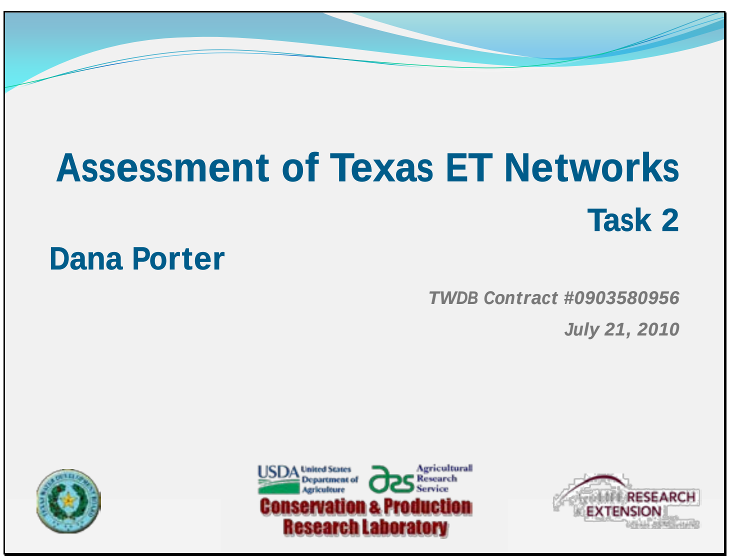
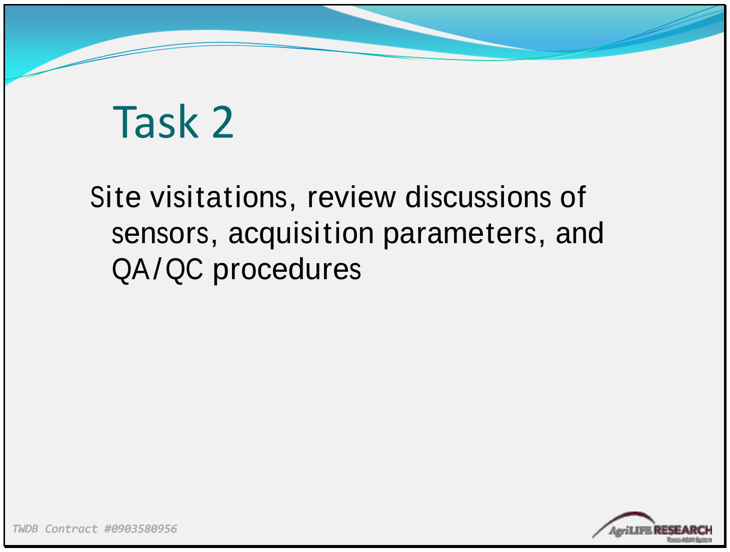


Slide 113



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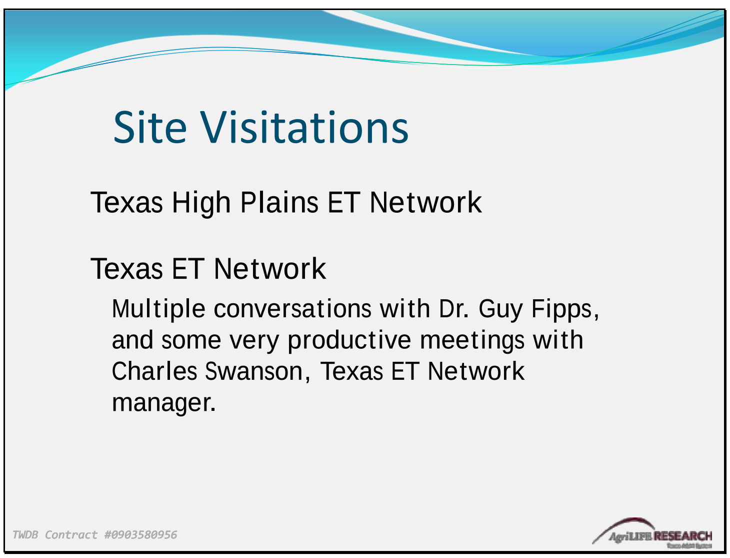

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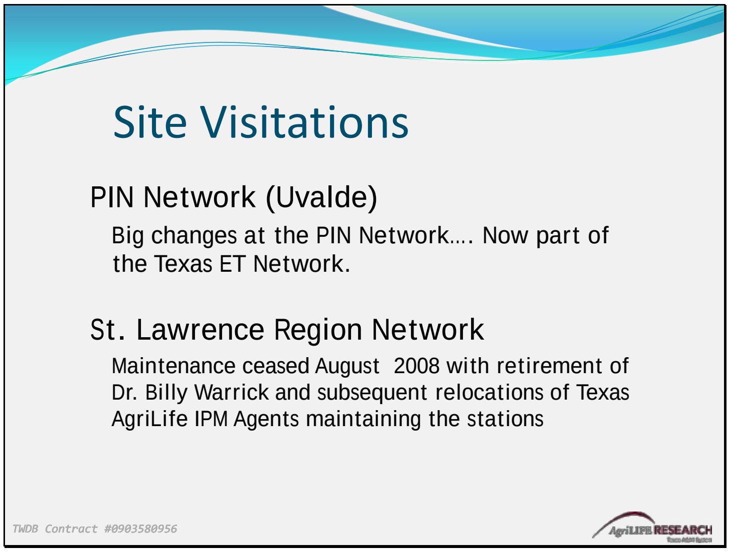

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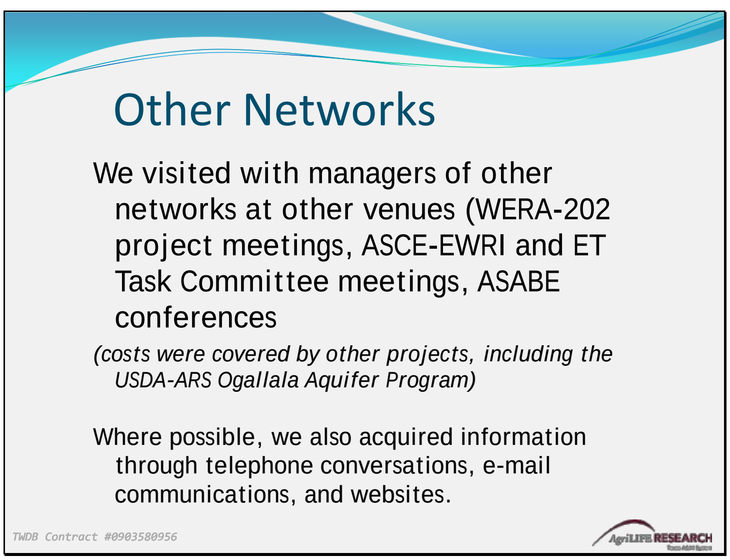

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Survey Questions

Categories

Data acquisition and management
Equipment used
Network
Technology transfer
Other

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Survey Questions

Data acquisition and management

Type of data (meteorological, climate parameters)
Storing (archiving) data
Frequency of data sequestration (seconds, minutes, hourly, daily)
Method of data sequestration (auto, manual)
Frequency of data output (matrix)
Interrogation interval
Daily summary output?
Data and units gathered - list

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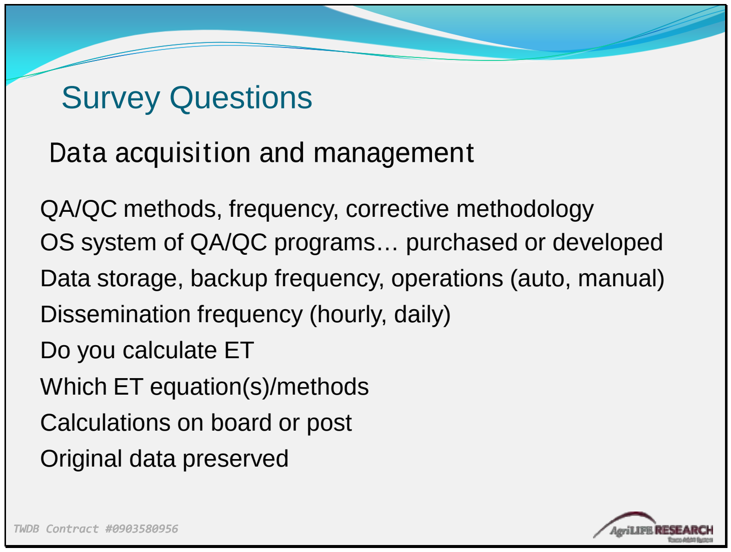

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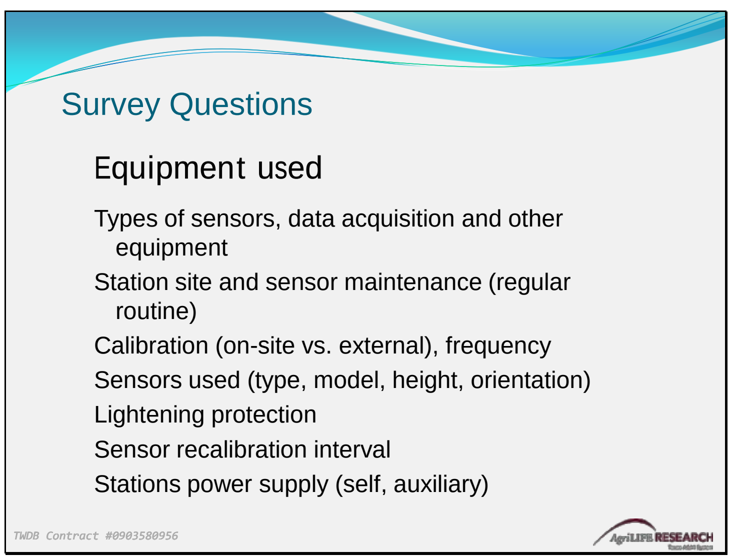

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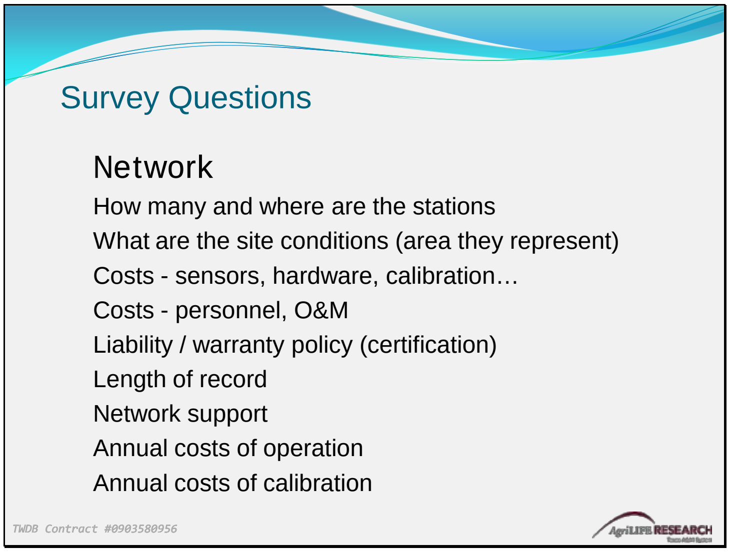

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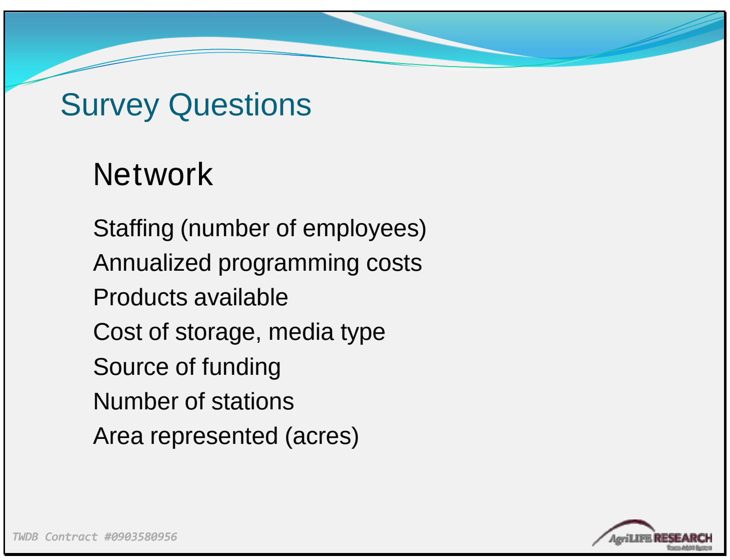

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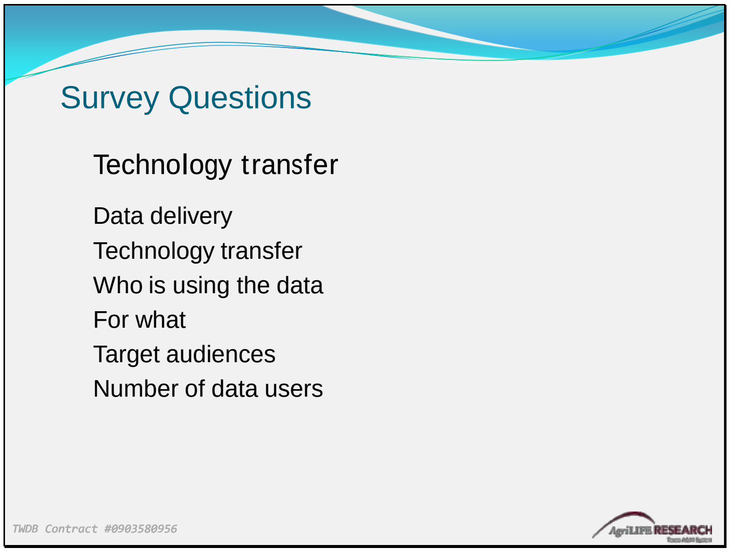

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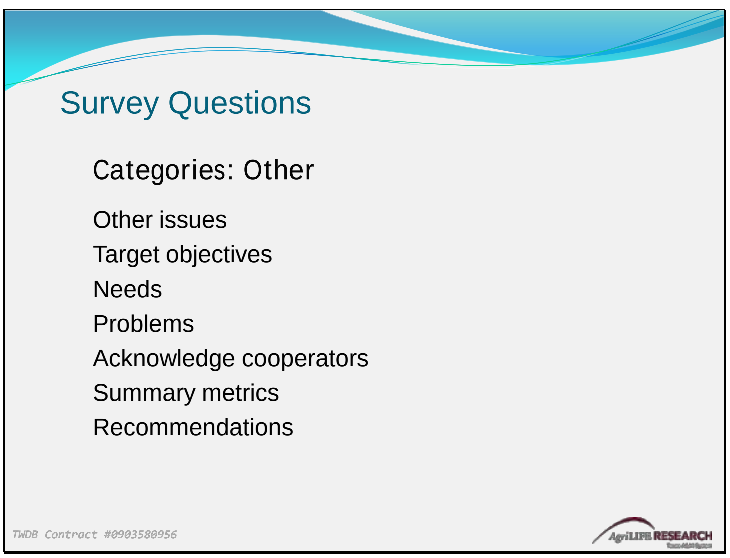

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TXHPET Measurements - typical

- Air temperature
- Relative humidity
- Wind speed (ht= 2m) and direction
- Solar radiation
- Precipitation
- Soil temperature at 2 and 6 inches
- Actual vapor pressure
- Vapor pressure deficit
- Standard deviation of wind direction
- Barometric pressure *

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TXHPET Weather Stations

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TXHPET Weather Stations

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TXHPET QA/QC

- Automated acquisition of all data parameters, as well as battery voltages, etc.
- Automated upload of data and calculations (ETr, Heat Units, crop growth models, etc.) to database
- Visual/graphical inspection of data – Don Dusek
  - Data anomalies (out of range values; trends that may indicate sensor problems)
  - Corrections are made as necessary
- Phone call/e-mail notification
  - Automated message to Don
  - “Don-activated” message to Thomas and Dana

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Texas ET Network Measurements

- Temperature
- Relative Humidity
- Solar Radiation
- Rainfall
- Wind speed

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Texas ET Network QA/QC

Cooperators agree to maintain station equipment according to network recommended schedules. Cooperators are asked to submit forms verifying maintenance schedules.

QA/QC database

Boundaries - upper and lower limits for data parameters
“Communication error" notifications

Error messages indicate if data are out of bounds or if cell phone doesn't pick up, etc.

Flags indicate need for visual inspection of data.

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The Crop Weather Program at Corpus Christi

Carlos Fernandez, Manager

- Some overlapping territory and stations with the Texas ET Network.

Information delivery is different, but the station network model is very similar. Stations are maintained by cooperators, generally county extension agents, cotton gins, agricultural producers

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Crop Weather Program (CWP) Measurements

- Temperature
- Relative humidity
- Solar radiation
- Wind speed and direction
- Soil temperature at 1, 3, and 12 inches
- Precipitation

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CWP Station - typical

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Crop Weather Program (CWP) QA/QC

Weather data
Automatically collected over land-lines and wireless networks several times daily

Data are checked for common errors
(out-of-range sensor values, data recording anomalies) and cross checked with other weather station

Data access requires user account/login

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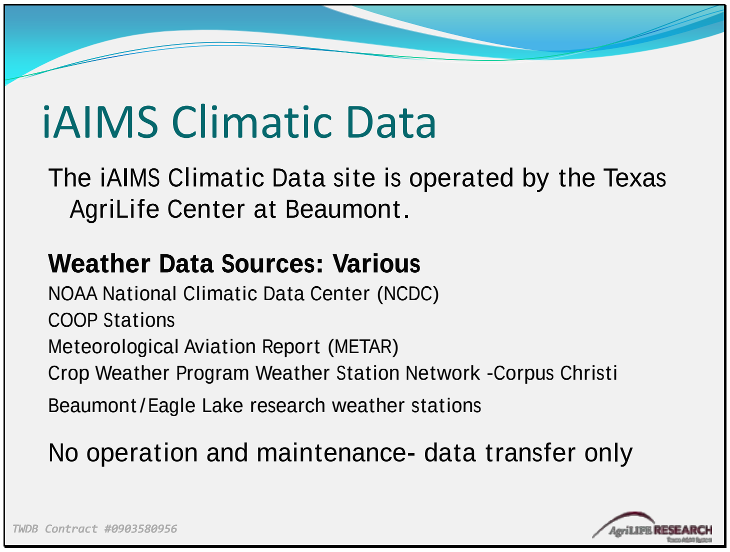

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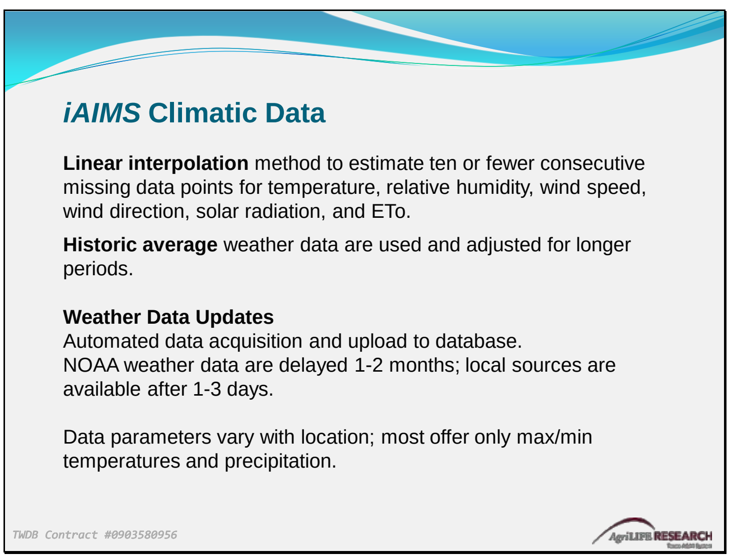

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San Angelo Network

This Network has been "decommissioned by default" since this project was initiated.

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Uvalde Precision Irrigators (PIN) Network

Between the initiation of this project and recent months, the PIN Network had fallen into disrepair due to lack of skilled / dedicated expertise resulting from personnel changes in Texas AgriLife Research and Texas AgriLife Extension.

Due to popular demand by end-users, and with some funding support from TWDB, several of the stations have been adopted by the Texas ET Network.

O&M, QA/QC will follow the Texas ET Network model .

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Other Networks – QA/QC

AgriMet (Northwestern US, Peter Palmer, Manager)

Visual Basic / MS EXCEL Spreadsheet program to generate graphical summaries of data for visual inspection

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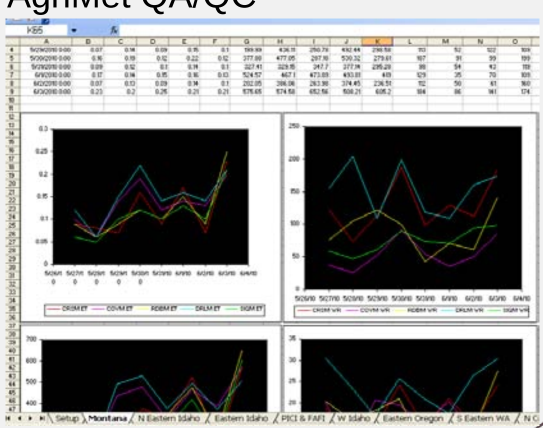
AgriMet QA/QC



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Source: Peter Palmer

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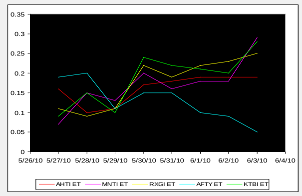
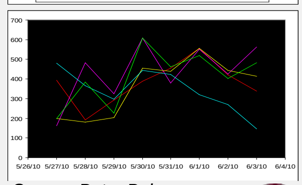
AgriMet QA/QC example

ET for weather stations, NE Idaho



SR data for those weather stations



Source: Peter Palmer

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Other Networks – QA/QC

http://mesowest.utah.edu/

MesoWest has been designed for use by National Weather Service meteorologists and other professionals for protection of life and property.

QA/QC applied to data as they are processed.
- **Range Checks for all variables**
- **Statistical Checks for temperature, relative humidity, and barometric pressure**

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***MesoWest* DATA MAXIMUM and MINIMUM FLAGGING CRITERIA**

Variable	Identifier	Minimum Value	Maximum Value
Pressure (*Mb*)	PRES	600.	1049.
Temperature (*Fahrenheit*)	TMPF	-75.	135
Dew Point (*Fahrenheit*)	DWPF	-75.	135
Relative Humidity (*%*)	RELH	0.	100
Wind Speed (*Knots*)	SKNT	0.	125
Wind Direction (*Degrees*)	DRCT	0.	360

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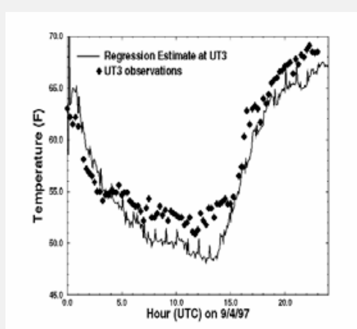
MesoWest statistical checks include comparison of the linear regression estimates of parameters to the observed data.



http://mesowest.utah.edu/

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MesoWest QA/QC data flags

Black/OK: data has passed all QC checks

Orange/Caution: some data have been flagged by the statistical check and should be used with caution

Red/Suspect: some data have been found to be outside reasonable bounds.

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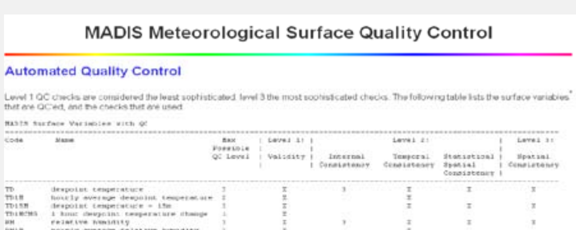
Other Networks – QA/QC

NOAA Meteorological Assimilation Data Ingest System (MADIS)
http://madis.noaa.gov/madis_sfc_qc.html

Validity of data range; internal, temporal, spatial and statistical consistency



MADIS Meteorological Surface Quality Control

Automated Quality Control

Level 1 QC checks are considered the least sophisticated, level 3 the most sophisticated checks. The following table lists the surface variables that are QC'ed, and the checks that are used.

Code	Name	Max Possible QC Level	Level 1: Validity	Level 2: Internal Consistency	Level 2: Temporal Consistency	Level 2: Statistical Spatial Consistency	Level 3: Spatial Consistency
TD	dewpoint temperature	[illegible]	X	X	X	X	X
[illegible]	hourly average dewpoint temperature	[illegible]	X		X		
[illegible]	dewpoint temperature - 15m	[illegible]	X		X	X	X
[illegible]	1 hour dewpoint temperature change	[illegible]	X				
RH	relative humidity	[illegible]	X	X	X	X	X
[illegible]	hourly average relative humidity	[illegible]	X		X		

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Other Networks: Oklahoma Mesonet

http://www.mesonet.org/

Standard-primary variables (measured at every site)

Air temperature measured at 1.5 meters above the ground
Relative humidity measured at 1.5 meters above the ground
Wind speed and direction measured at 10 meters above the ground
Barometric pressure
Rainfall
Incoming solar radiation
Soil temperatures at 10 cm depth under natural sod cover and bare soil

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Other Networks: Oklahoma Mesonet

http://www.mesonet.org/

Secondary measurements: (at most, but not all sites)

Air temperature at 9 meters above the ground
Wind speed at 2 and 9 meters above the ground
Soil moisture at 5, 25, and, 60 centimeters below the ground
Soil temperatures at 5 and 30 cm depths under natural sod cover
Soil temperature at 5 cm depth under bare ground

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Oklahoma Mesonet QA/QC:

Laboratory calibration: All sensors are calibrated in the laboratory to validate or improve upon factory calibrations.

On-site inter-comparison: Field sensors are compared annually with portable calibrated sensors.

Automated QA software includes numerous algorithms to evaluate all data received from remote stations.

Manual QA: Meteorologists use manual techniques to complement automated QA

- Analysis of monthly statistics to detect sensor drift or bias
- Meteorologists communicate errors to field technicians to correct problems.

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Additional QA/QC Procedures and Guidelines

Allen, Richard G., Luis Pereira, Dirk Raes, and Martin Smith. 1998. FAO Irrigation and Drainage Paper No. 56.

- Measuring and assessing integrity of weather data
- Correction of weather data observed at non-reference weather sites to compute ETo.

Allen, Richard G., et. al. 2005. ASCE-EWRI Standardization of Reference Evapotranspiration. American Society of Civil Engineers.

- Weather data integrity assessment and station siting
- Estimating missing climatic data

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Additional QA/QC Procedures and Guidelines

Memo on **Quality Assessment and Control of Automated Weather Data** to Managers of Agricultural Weather Networks and Associated Weather Data Systems from the Technical Committee on Evapotranspiration in Irrigation and Hydrology of the Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE) April 1, 2009

http://www.kimberly.uidaho.edu/water/asceewri/memo01Apr09_QAQC.pdf

***ASABE* Engineering Practice 505: "*Measurement and Reporting Practices for Automatic Agricultural Weather Stations*" (ASAE, 2004).** This standard provides specifications for sensor accuracy, resolution, placement and monitoring, as well as intervals and procedures for sensor maintenance and calibration.

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Common Issues and Concerns

Funding stability

Staffing issues

Sensor accuracy and maintenance

Telecommunications reliability

Data QA/QC

Data management and delivery

Standardization (siting, data units, quality…)

Need for education to support appropriate application/interpretation of the information

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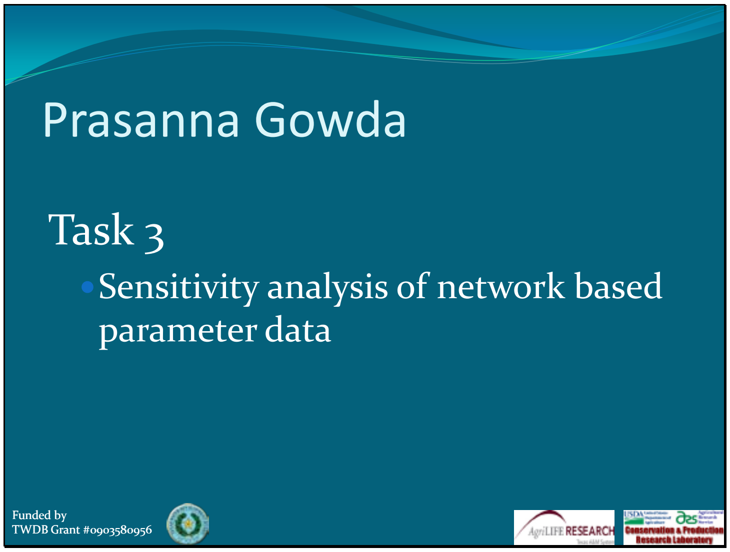

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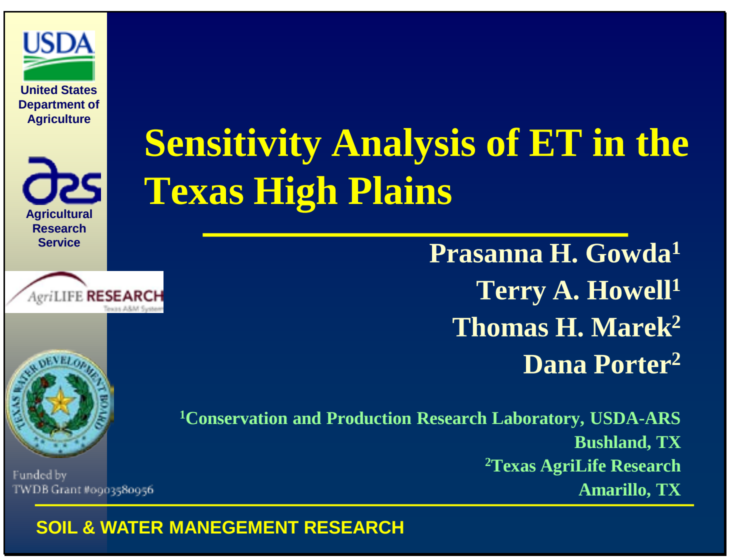

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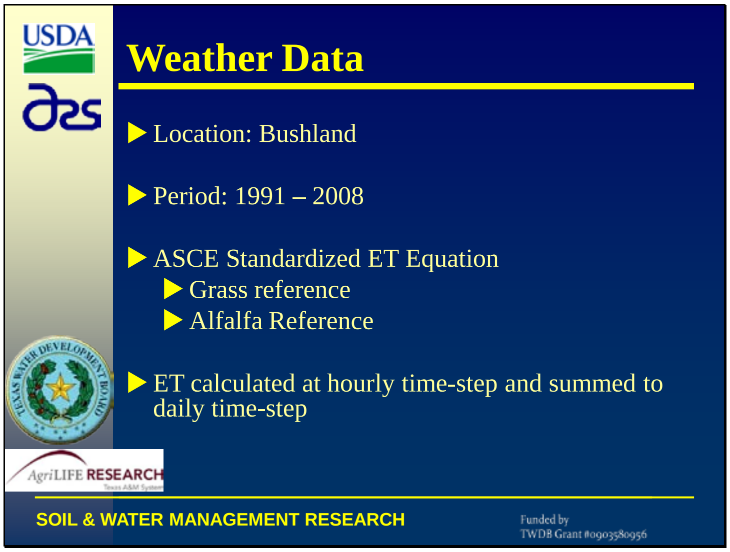

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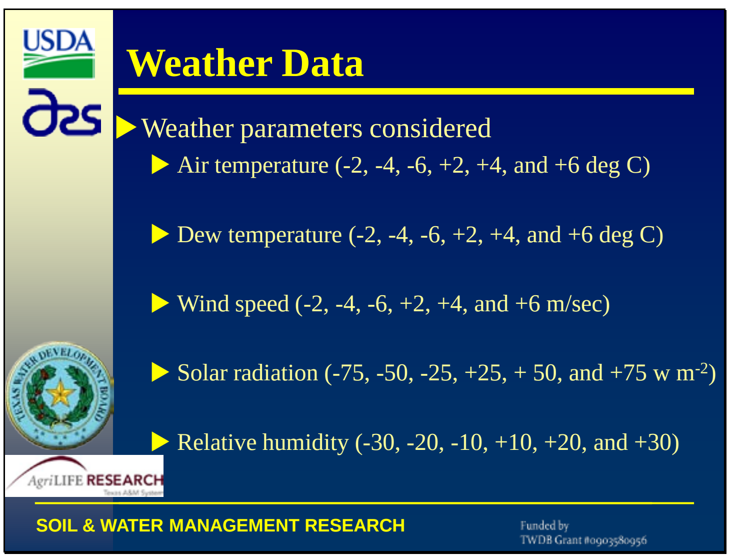

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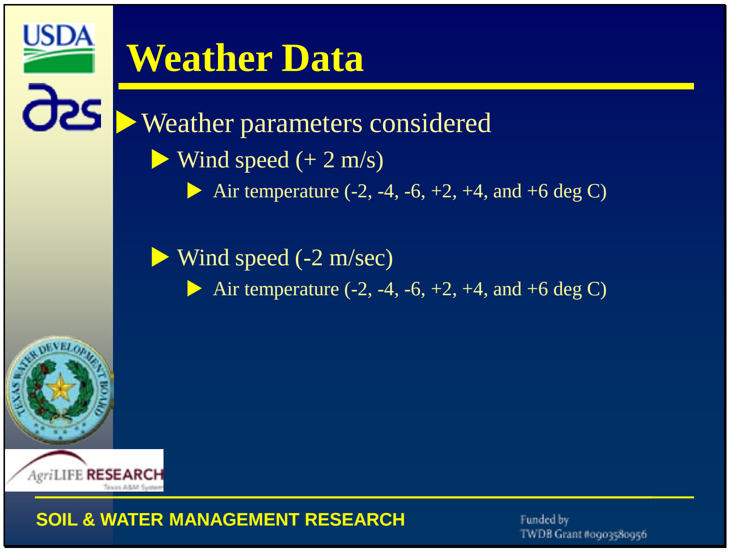

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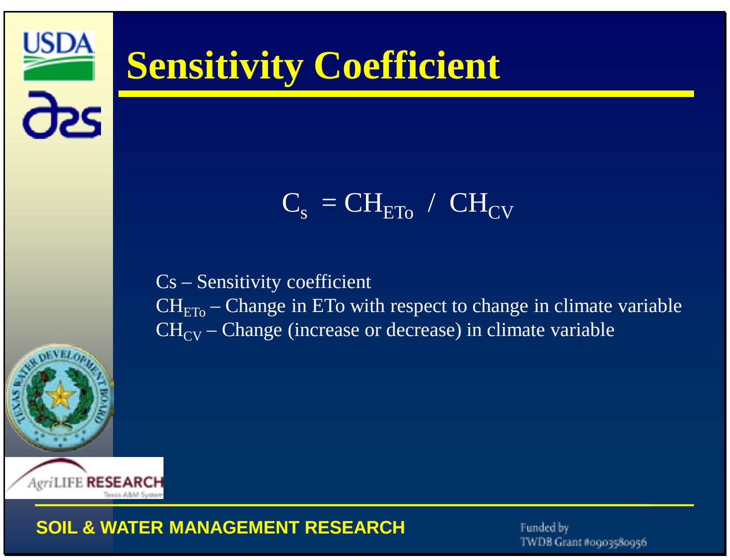

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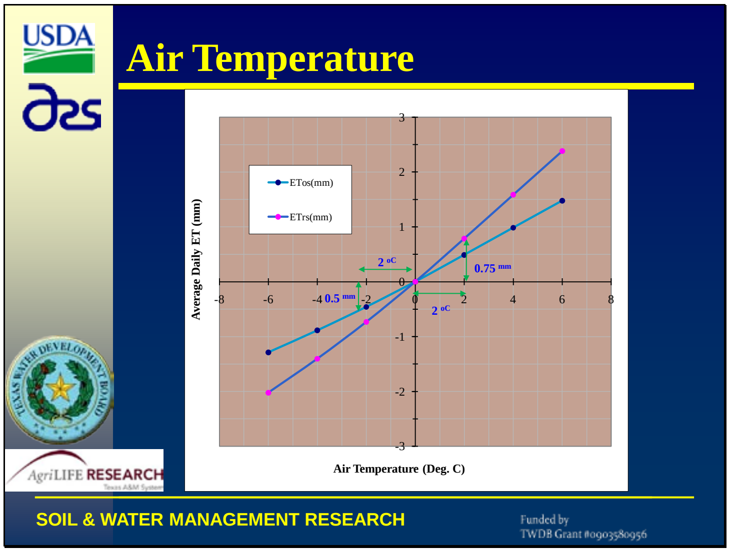

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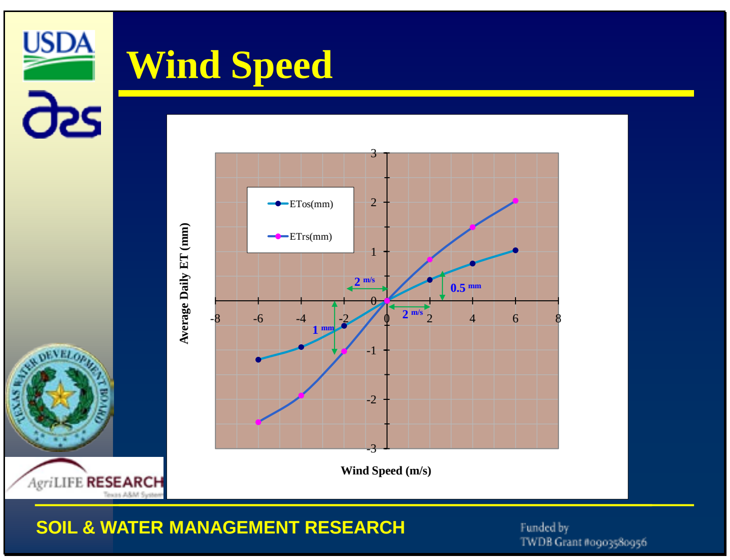

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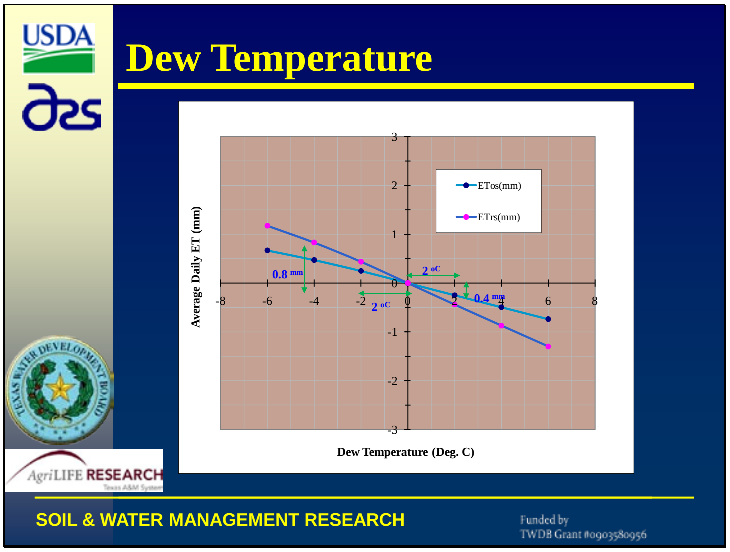

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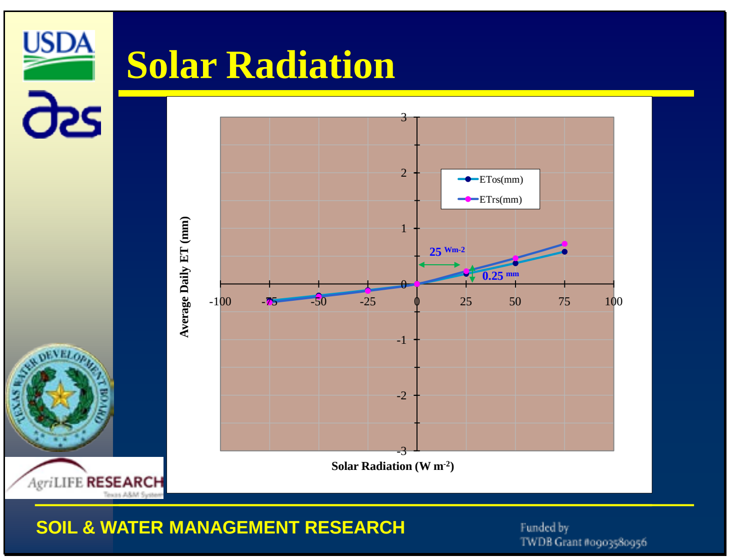

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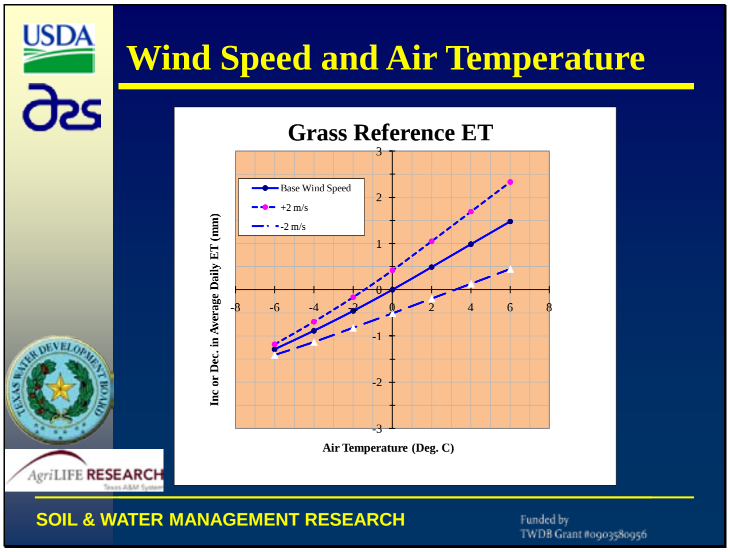

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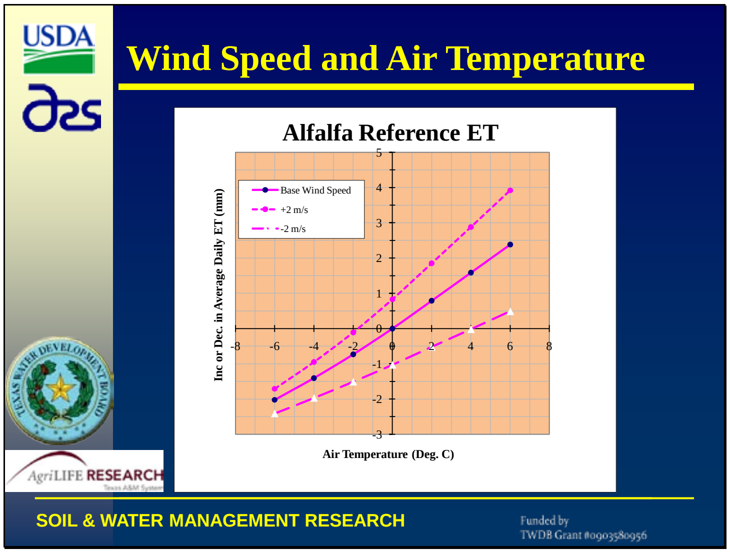

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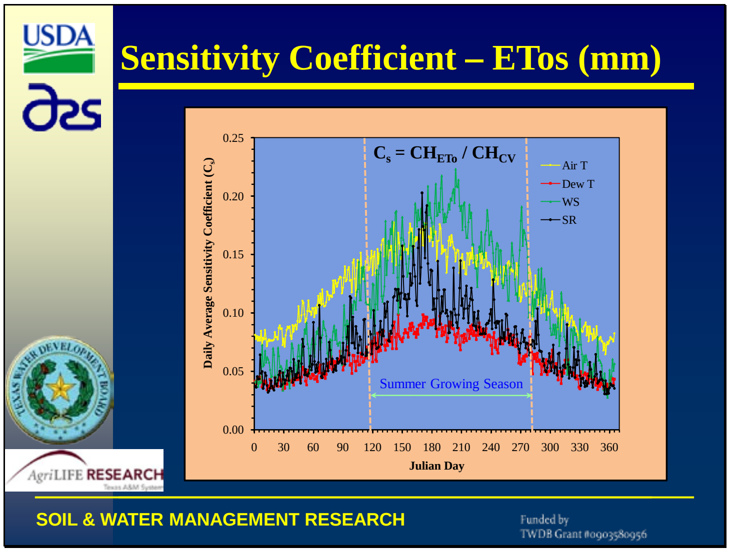

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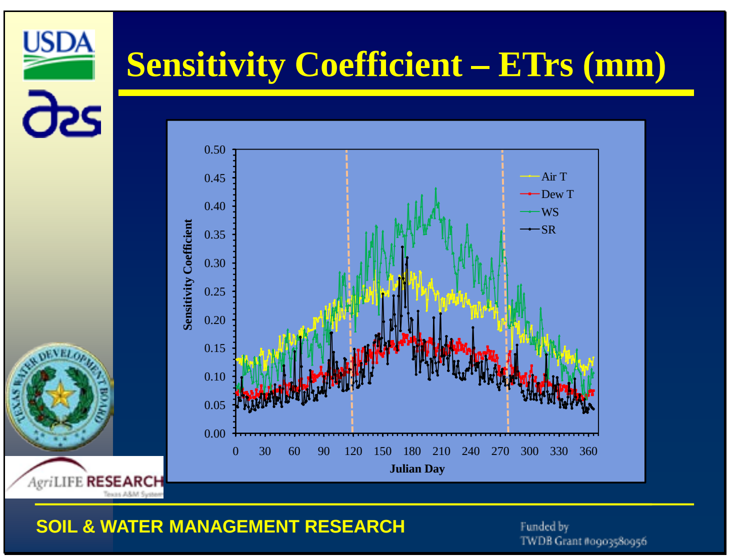

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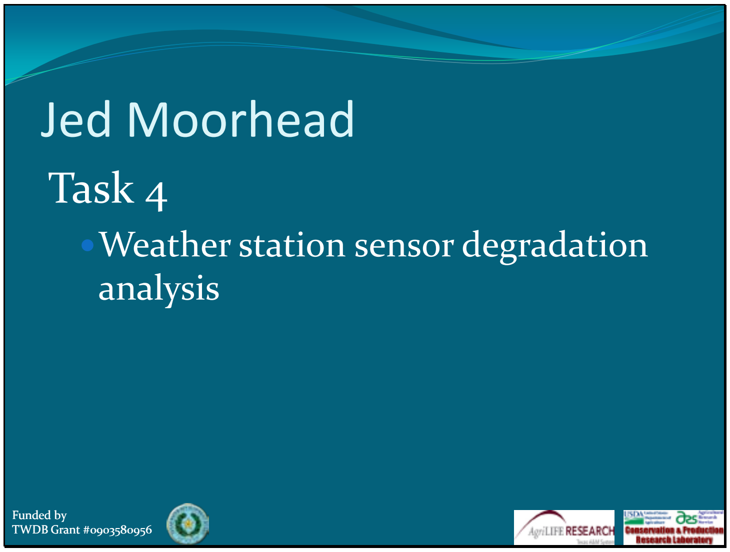

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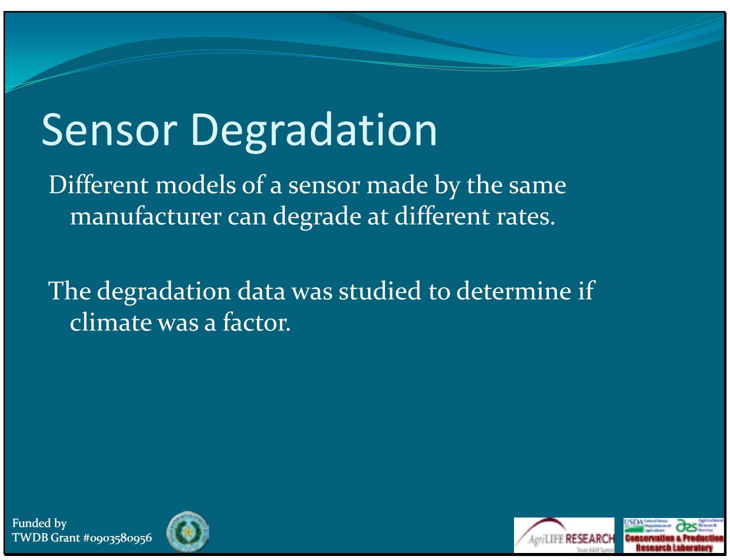

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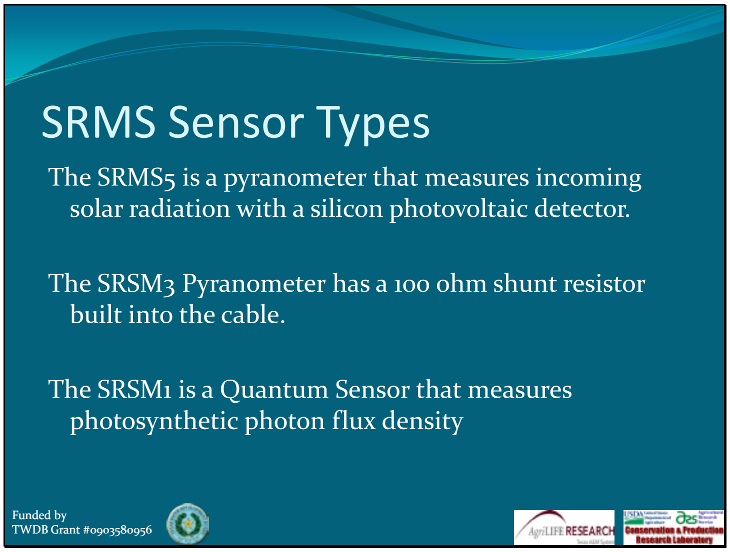

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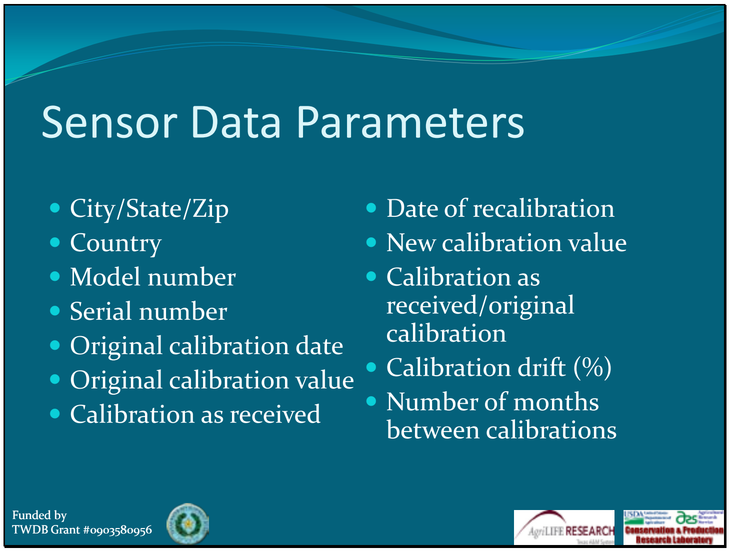

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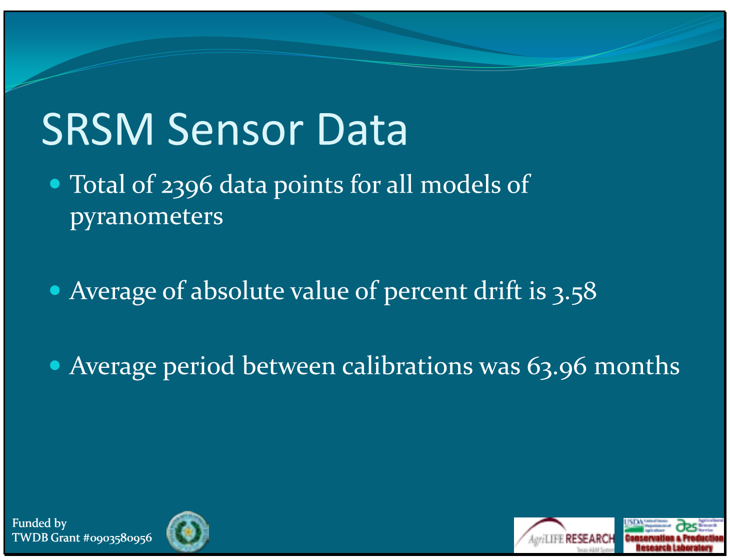

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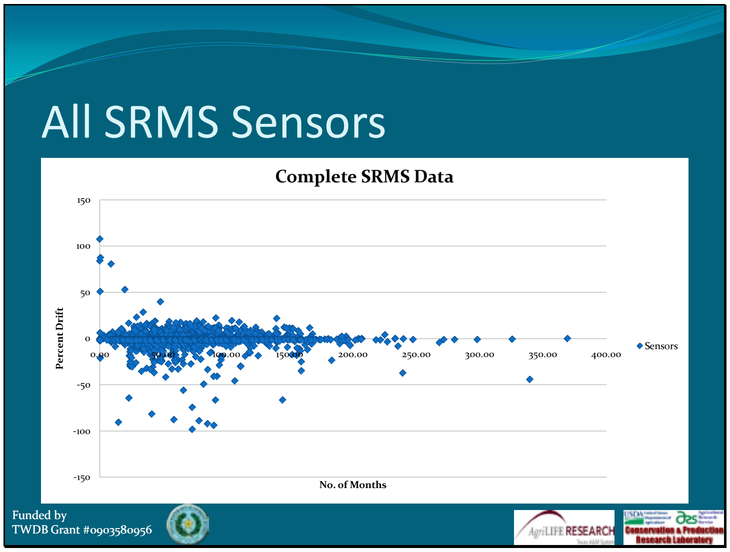

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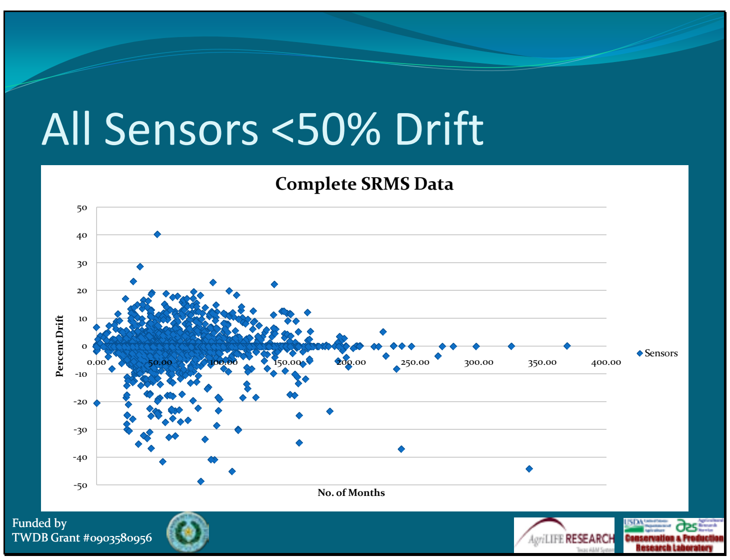

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SRMS2 Pyranometer

- 30 data points
- Average absolute value of percent drift of 14.08
- Average period between calibrations of 101.11 months
- Only 1 unit with zero drift

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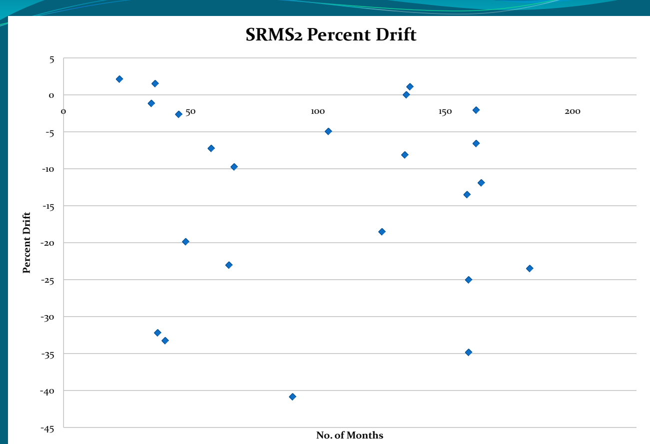

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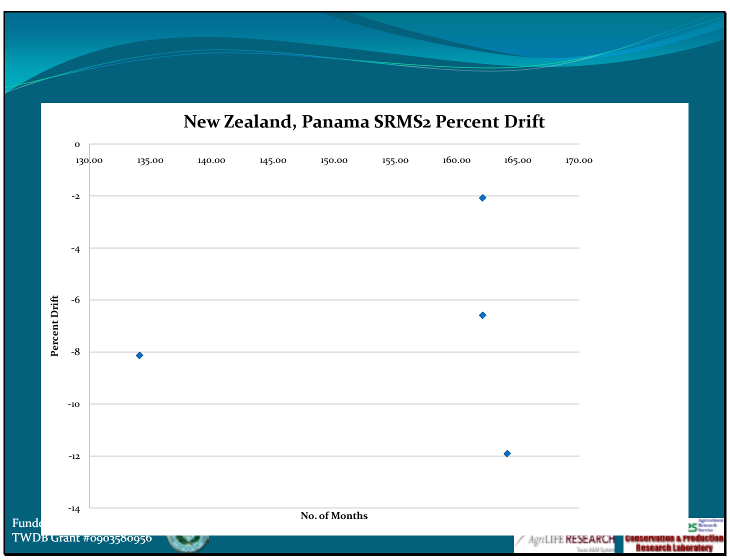

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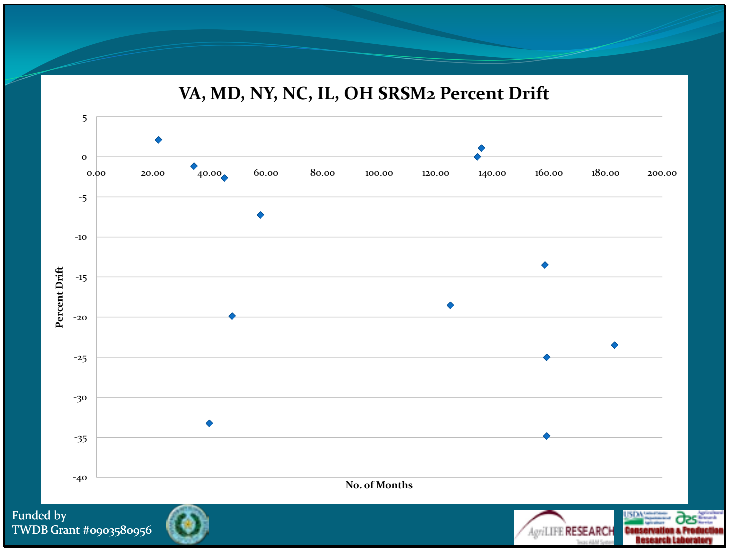

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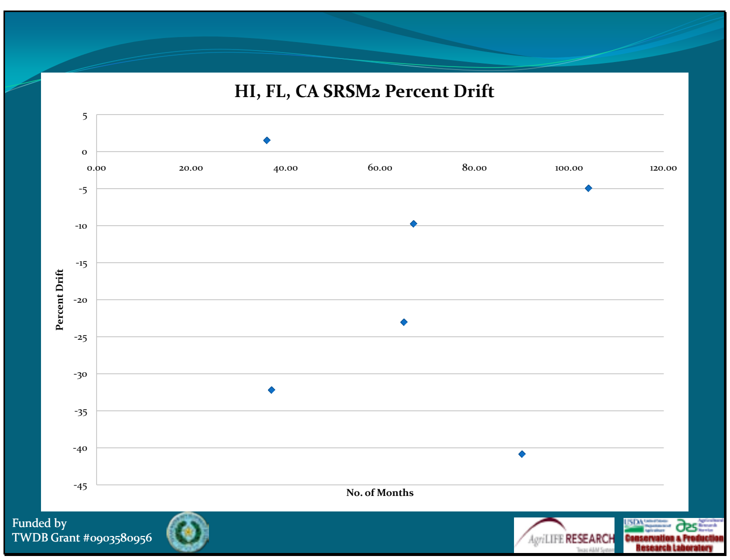

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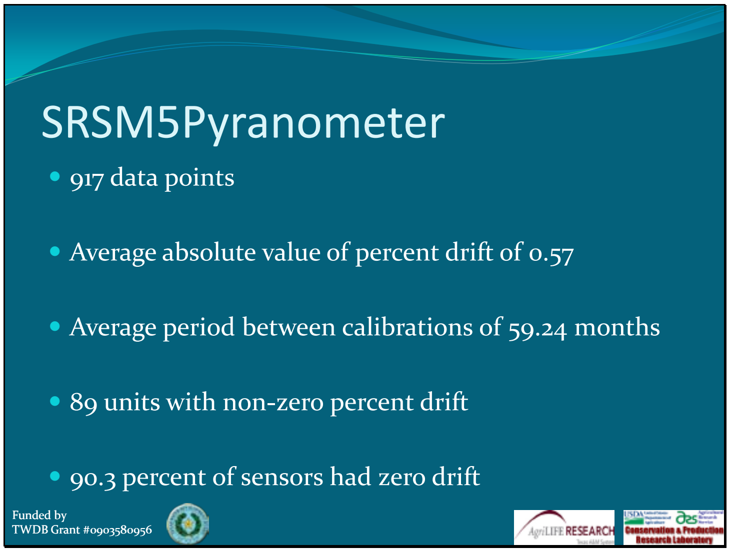

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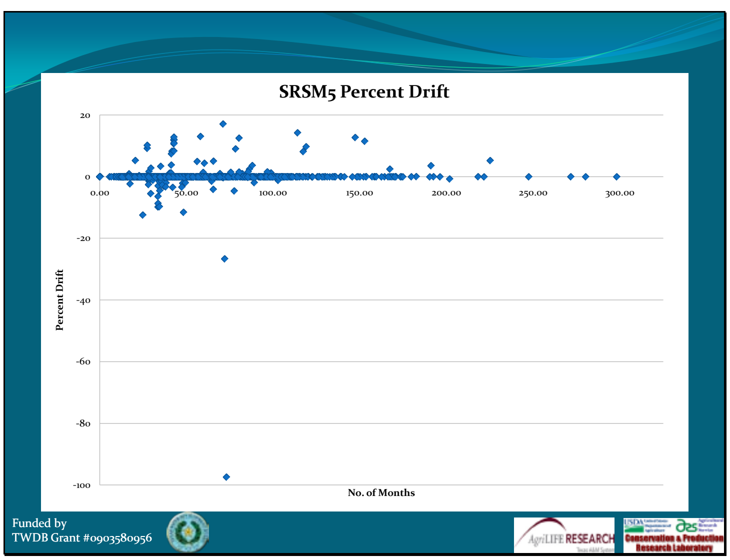

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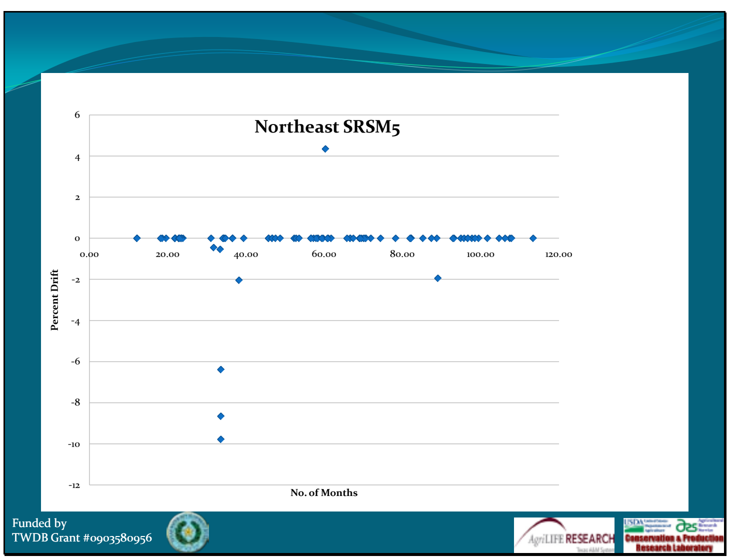

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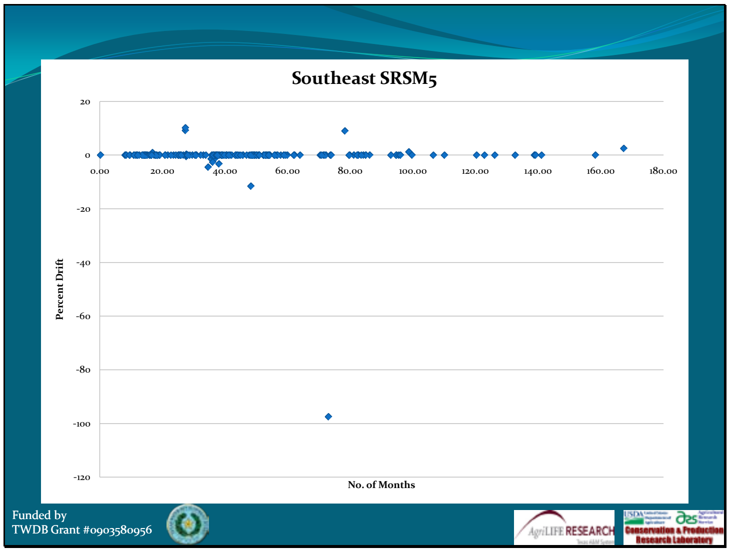

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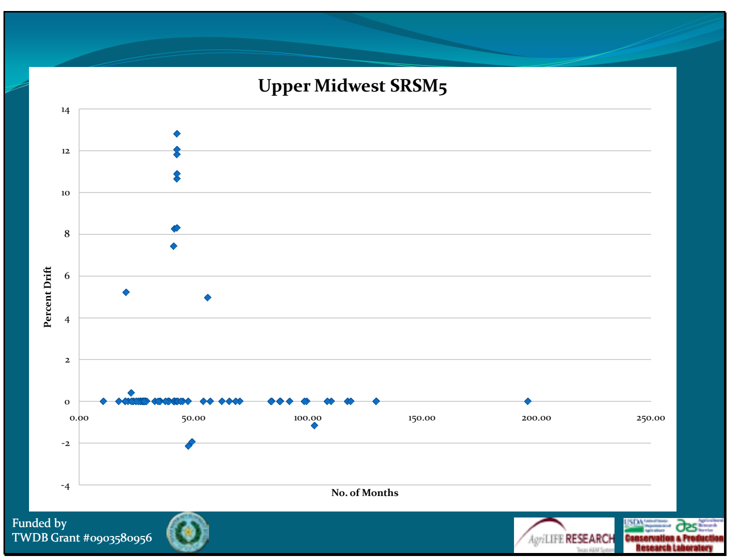

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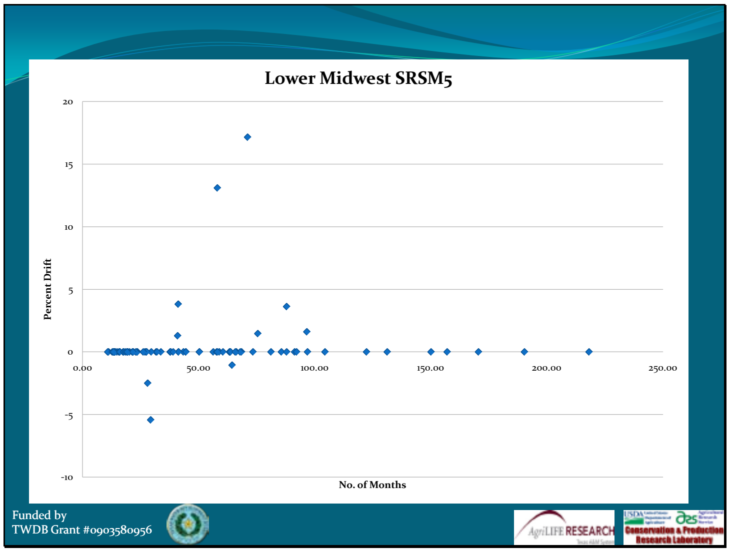

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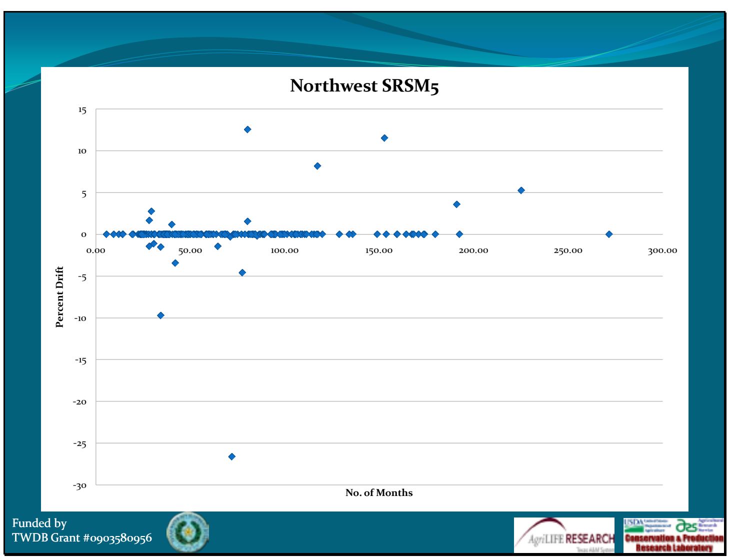

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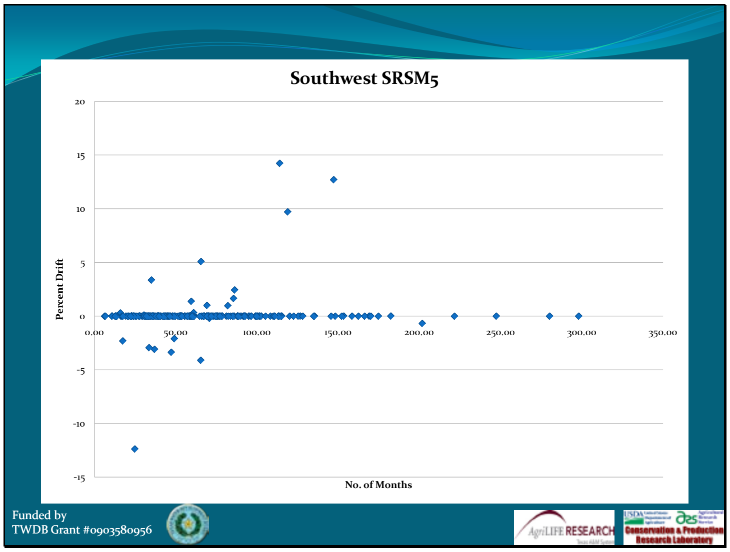

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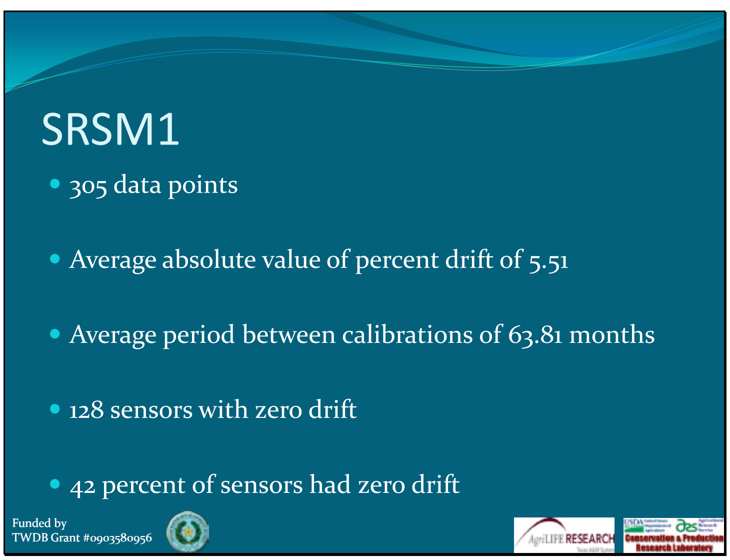

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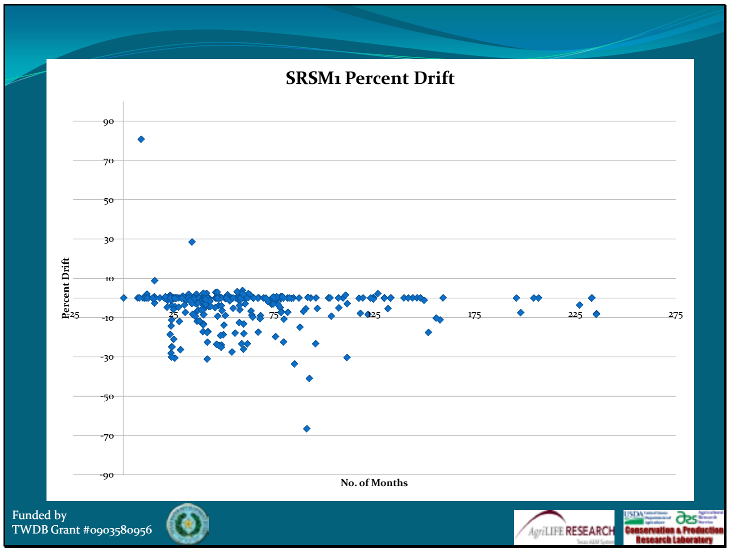
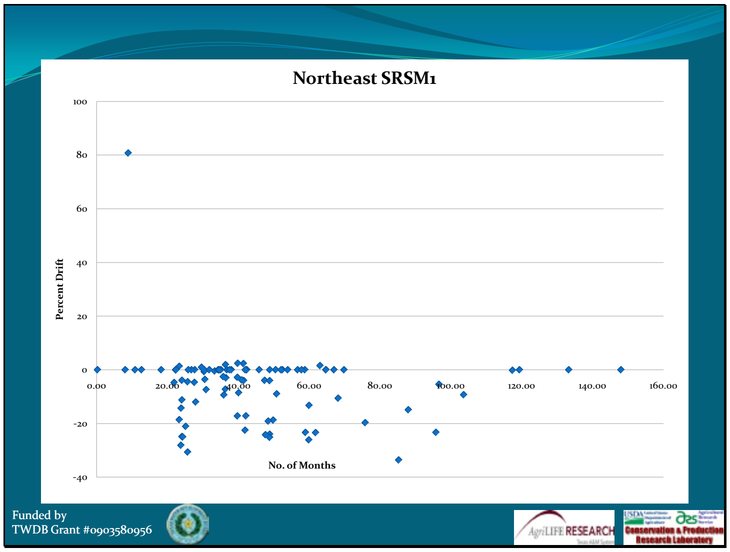


Slide 192

Slide 193



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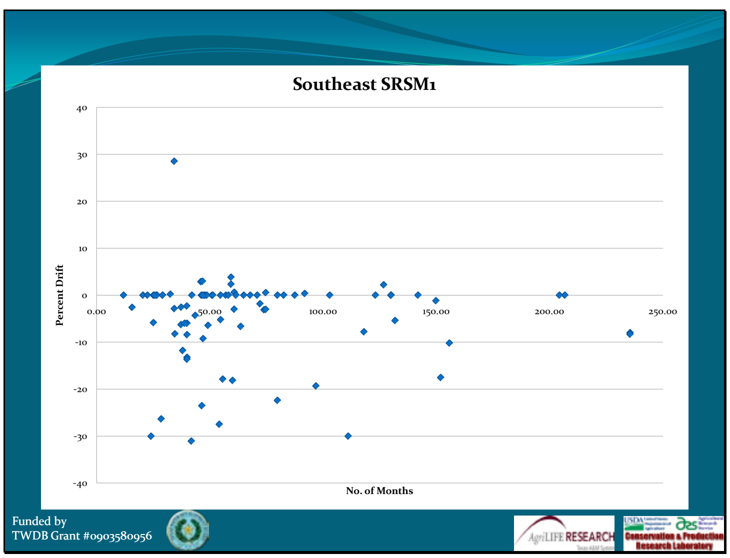

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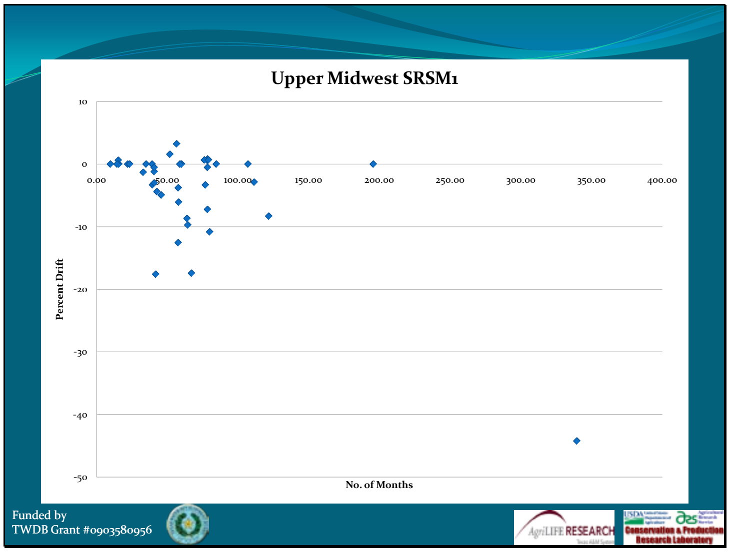

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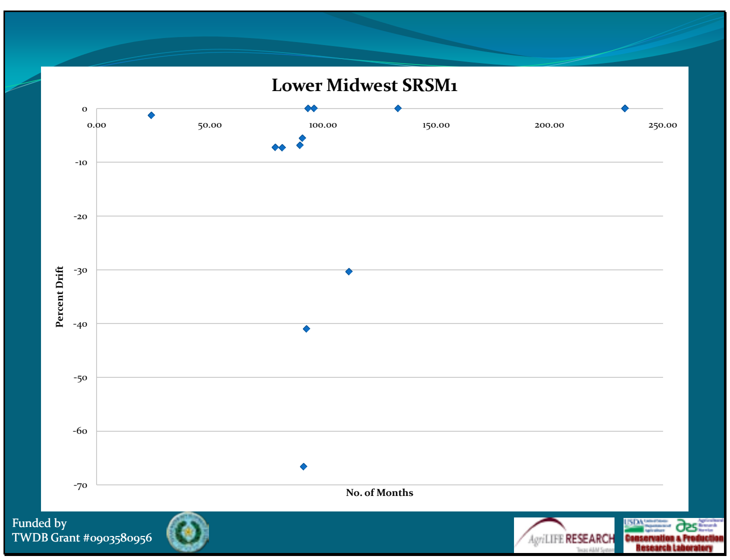

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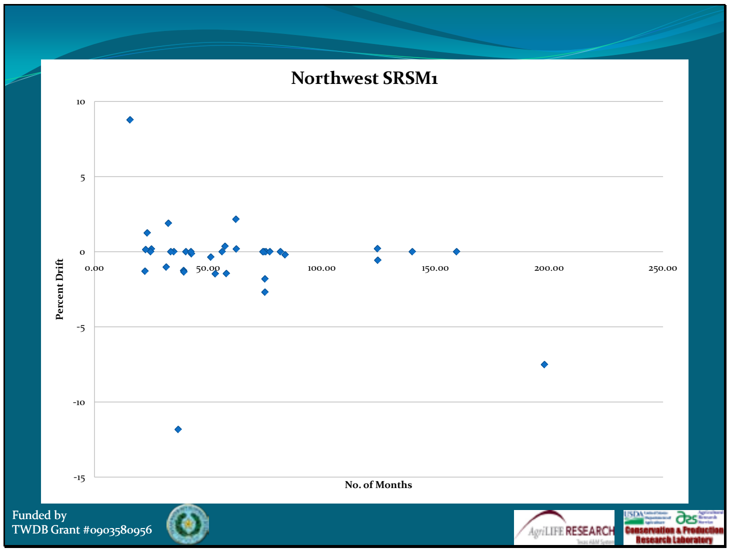

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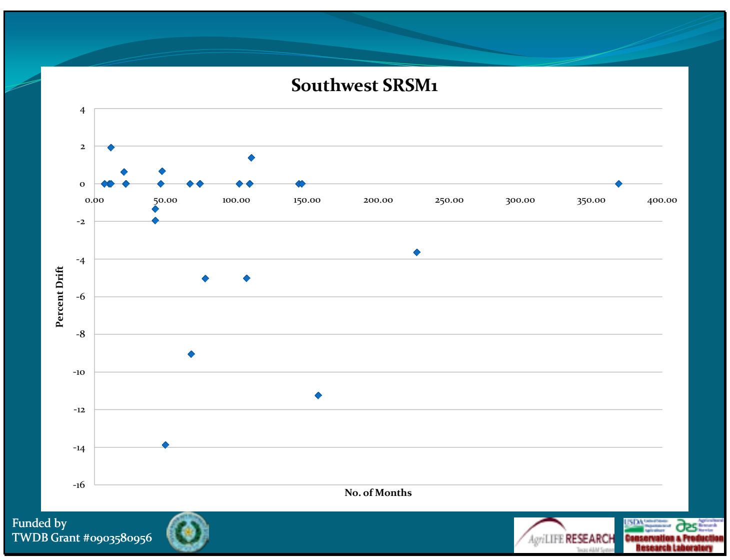

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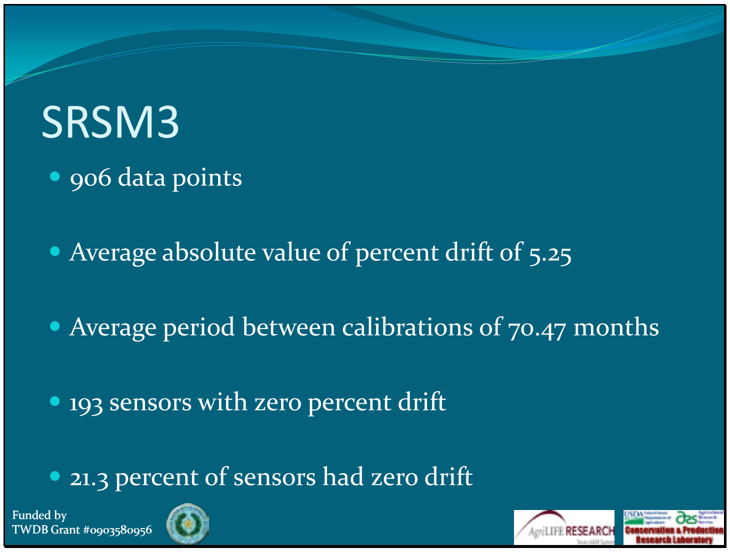

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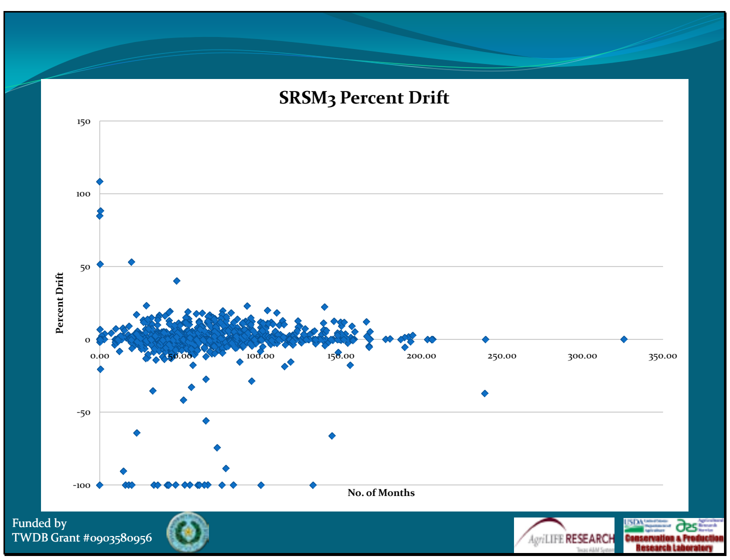
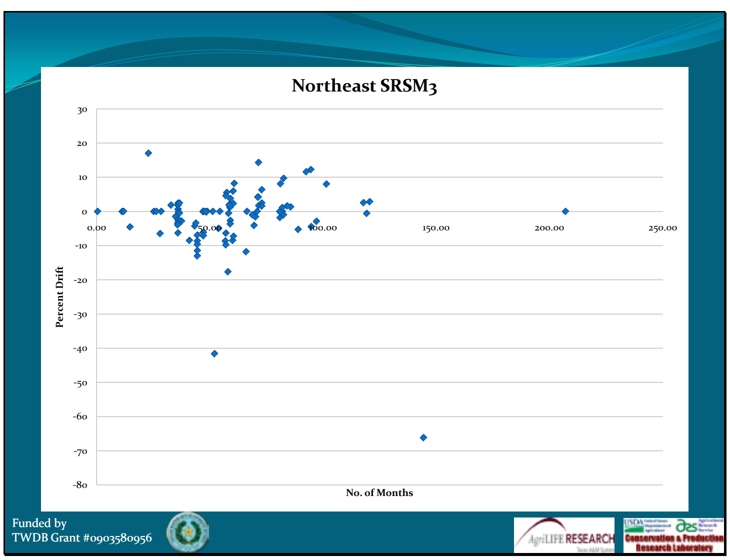


Slide 201

Slide 202



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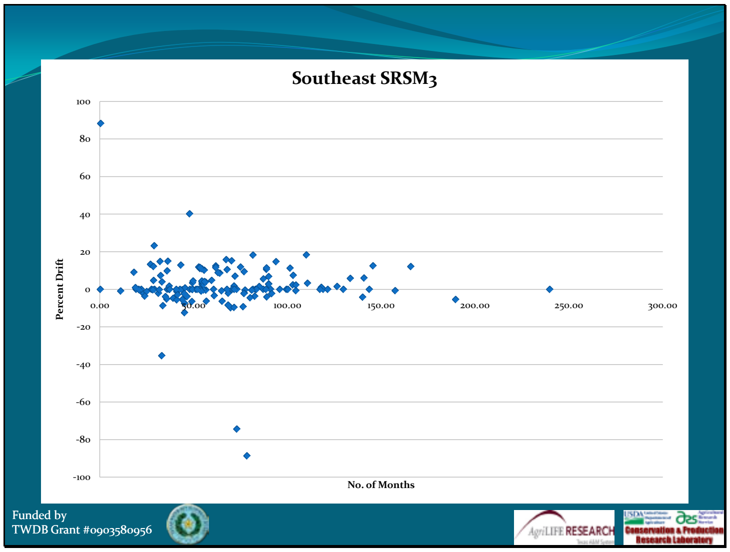

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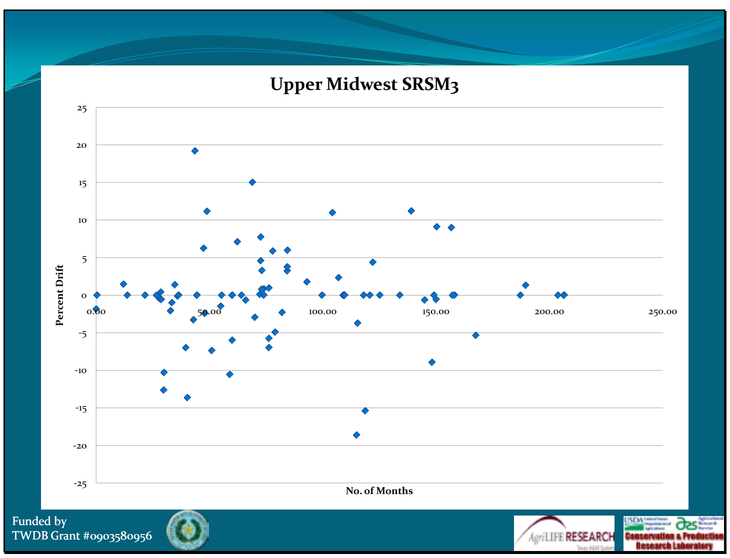

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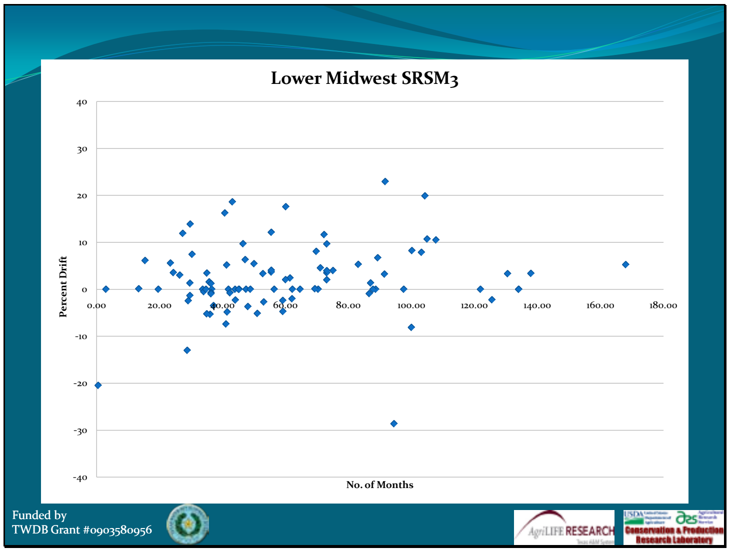

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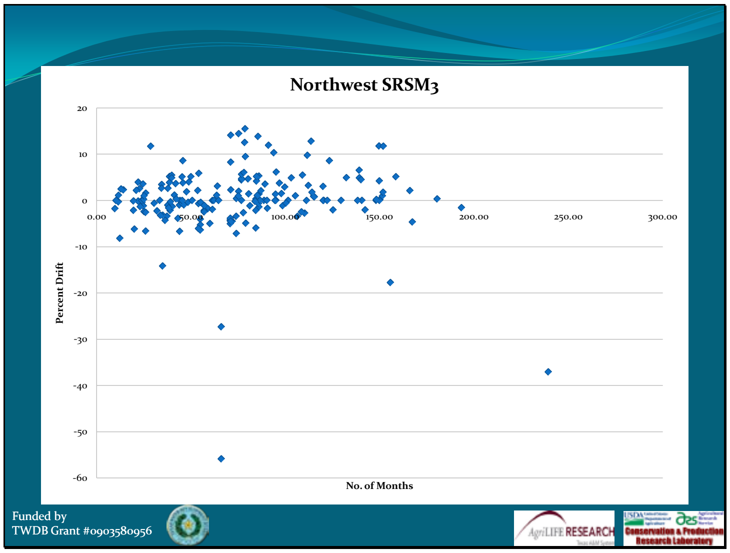

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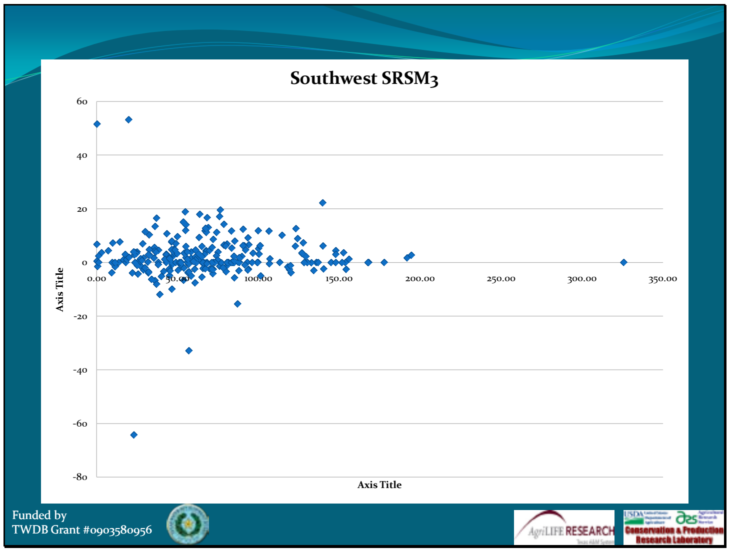

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SRSM4

- 253 data points
- Average absolute value of percent drift of 5.53
- Average period between calibrations of 54.47 months
- Only 2 sensor with zero drift
- 99.2 percent of sensors had drift

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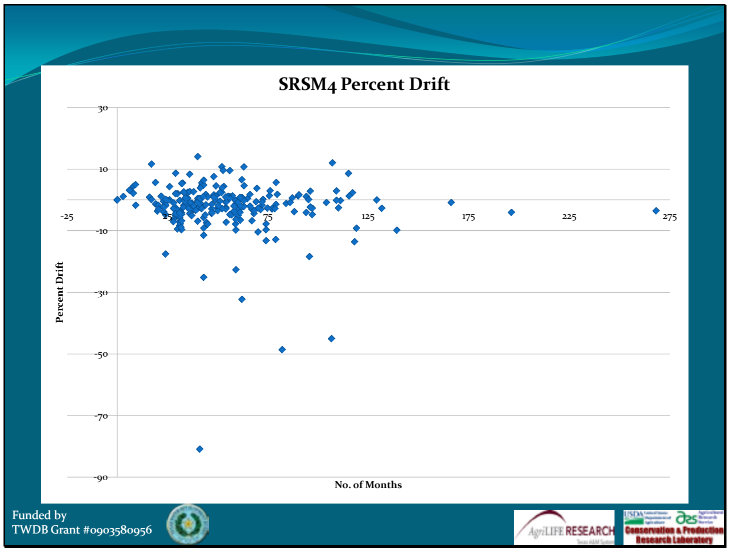
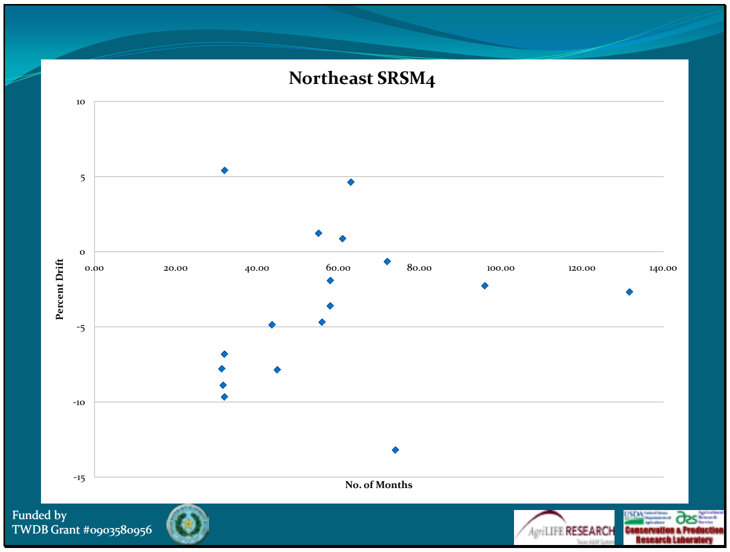
Slide 209



Slide 210

Slide 211



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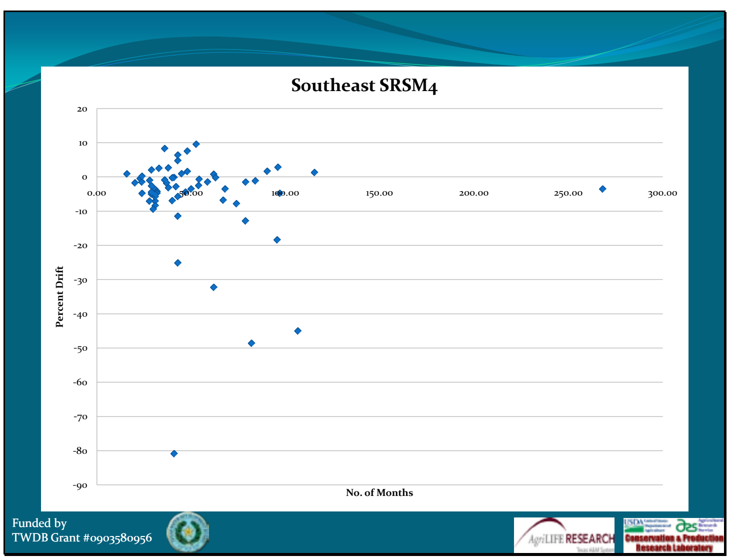

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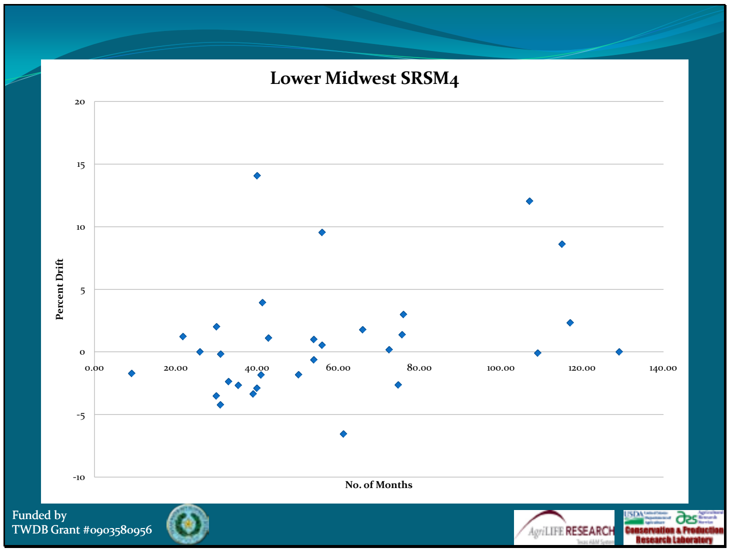

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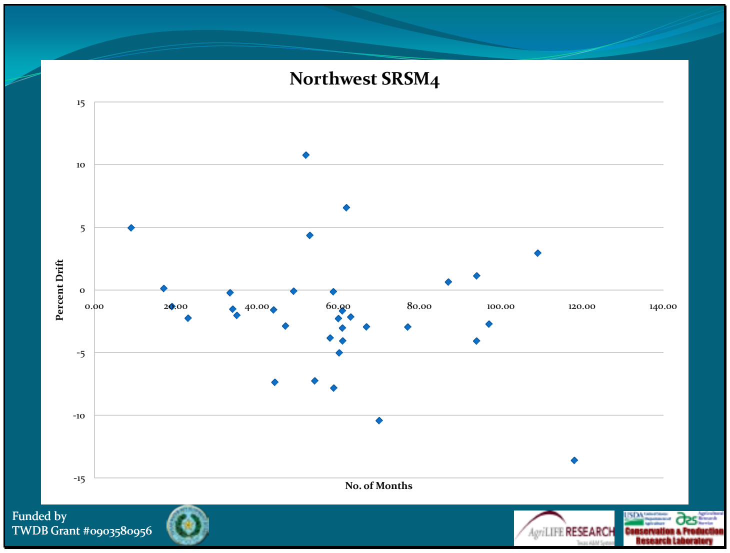

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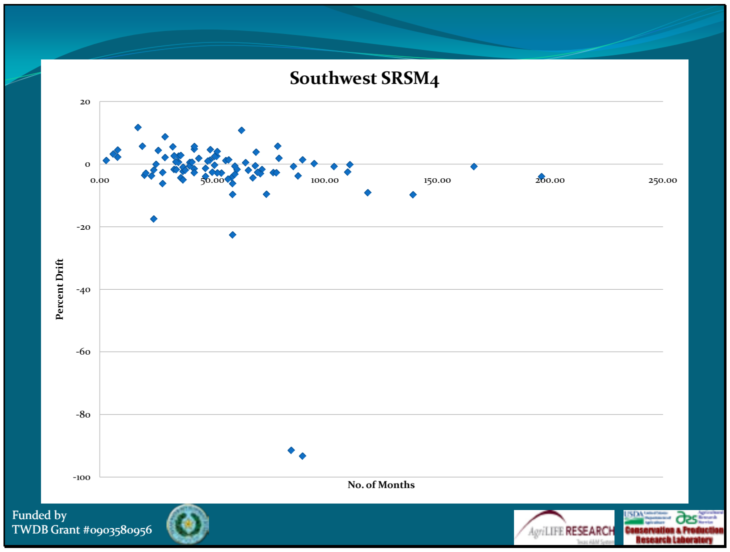

Slide 216

Climate

The data were separated by region, which were then analyzed

No correlation was found between sensor degradation and climate.

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SRMS Climate Data

Model Number and Region	Average % drift	Average No. of Months	No. of Sensors w/ 0 Drift	Total Sensors	% With 0 Drift
SRSM1 NE	7.5	45	43	98	43.9
SRSM1 SE	5.7	69	35	84	41.7
SRSM1 UMW	4.4	67	13	41	31.7
SRSM1 LMW	11.1	120	7	15	46.7
SRSM1 NW	1.3	63	13	36	36.1
SRSM1 SW	1.9	82	17	29	58.6
SRSM2 PANAMA	7.2	156	0	5	0.0
SRSM2NE	14.1	100	1	13	7.7
SRSM2 HI,FL,CA	18.7	67	0	7	0.0
SRSM3NE	4.9	59	20	99	20.2
SRSM3 SE	7.4	66	42	158	26.6
SRSM3 UMW	3.4	86	34	90	37.8
SRSM3 LMW	6.0	61	21	94	22.3
SRSM3 NW	3.9	74	26	192	13.5
SRSM3 SW	4.7	69	50	253	19.8
SRSM4 NE	5.1	56	0	17	0.0
SRSM4 SE	7.6	51	0	62	0.0
SRSM4 LMW	3.1	57	2	31	6.5
SRSM4 NW	3.8	59	0	33	0.0
SRSM4 SW	5.6	55	0	87	0.0
SRSM5 NE	0.4	56	87	95	91.6
SRSM5 SE	0.8	47	190	206	92.2
SRSM5 UMW	1.3	51	64	77	83.1
SRSM5 LMW	0.6	53	71	81	87.7
SRSM5 NW	0.5	70	175	196	89.3
SRSM5 SW	0.3	67	237	259	91.5

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Narrowing The Field

Since no trends were found for all sensors, the data were separated into those that had been recalibrated within 24 months.

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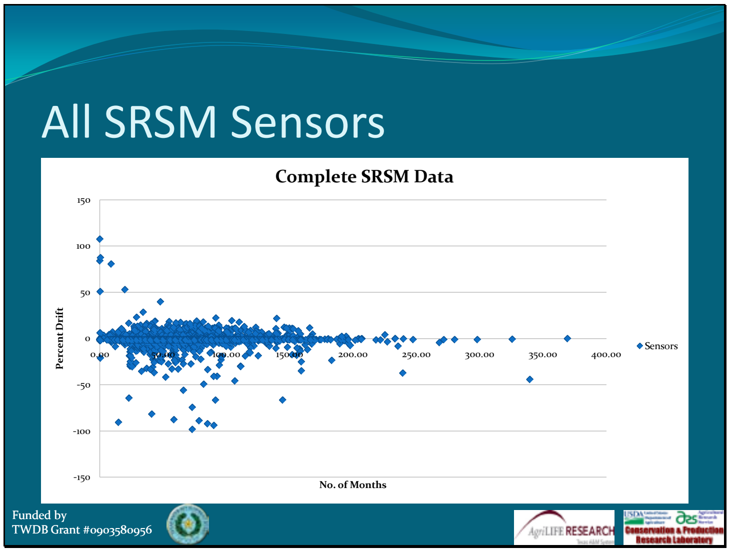

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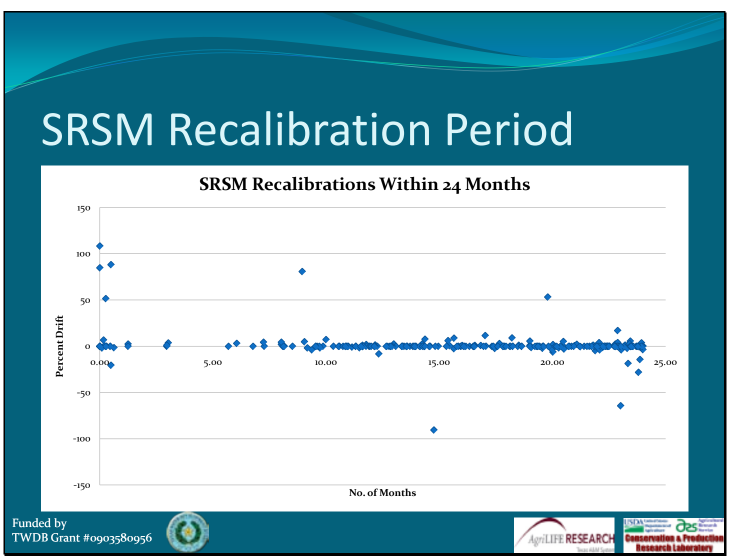

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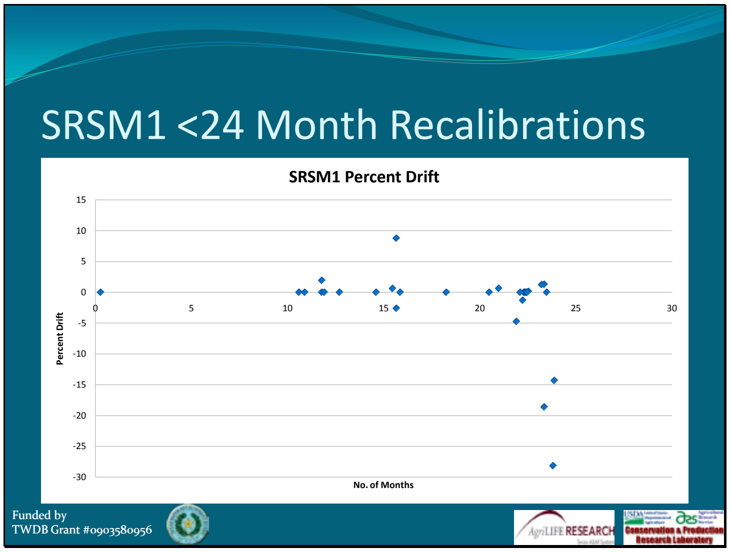

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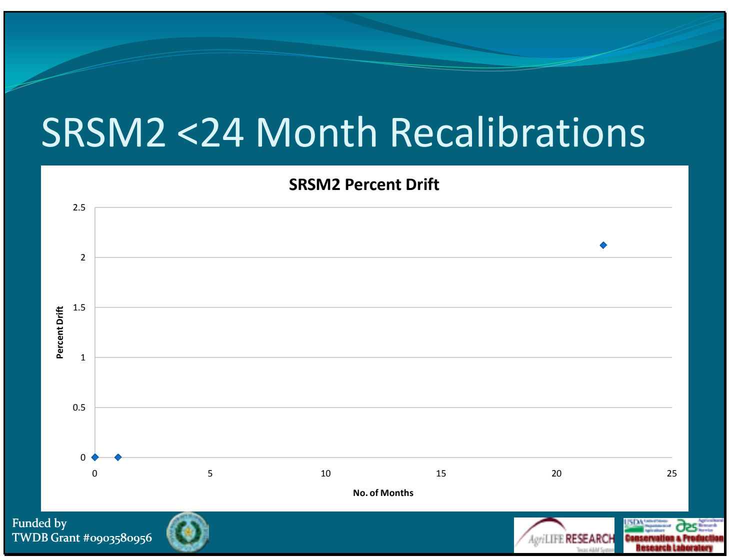

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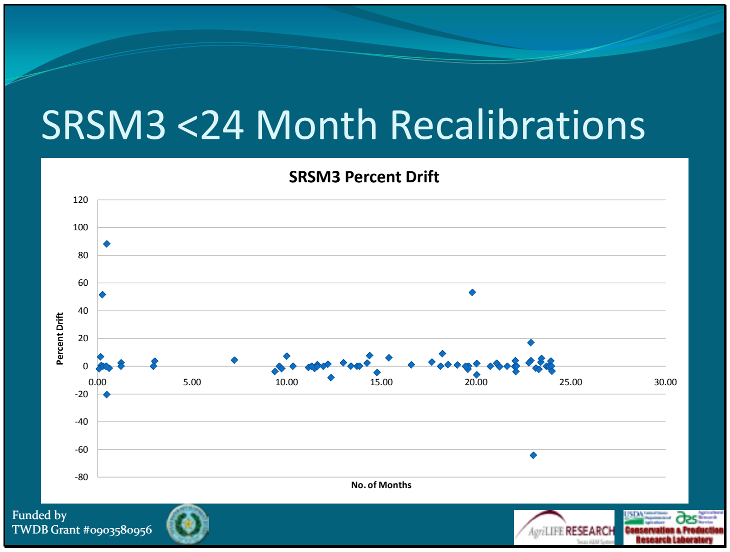

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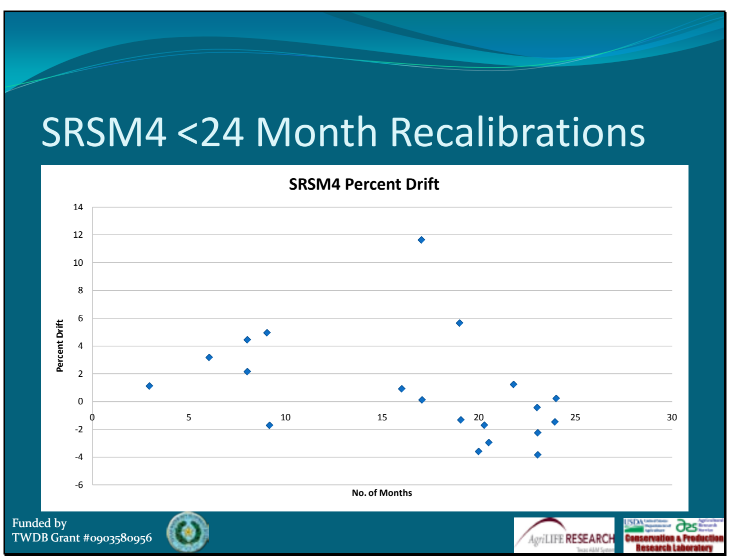

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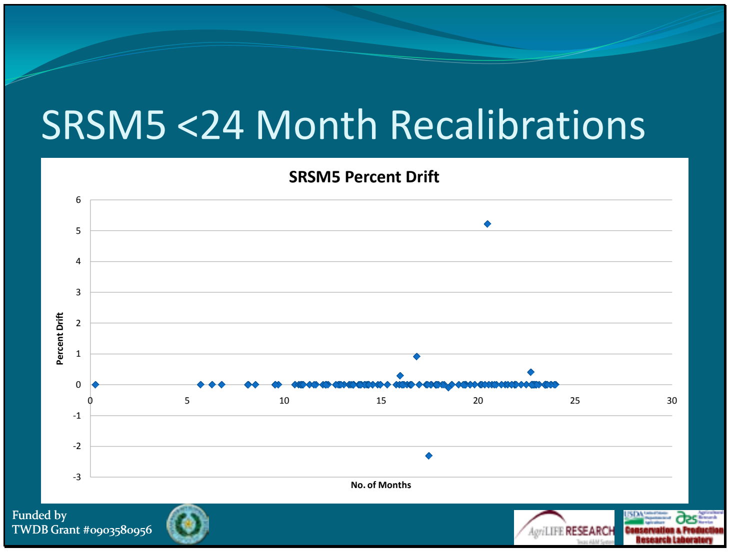

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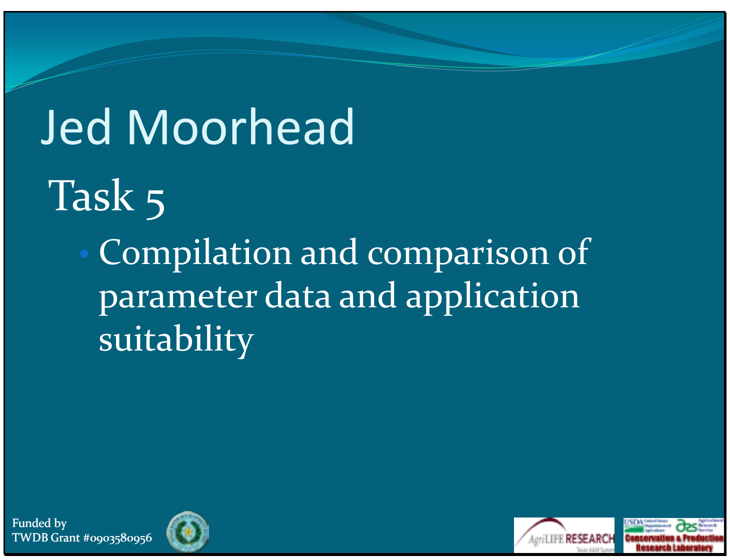

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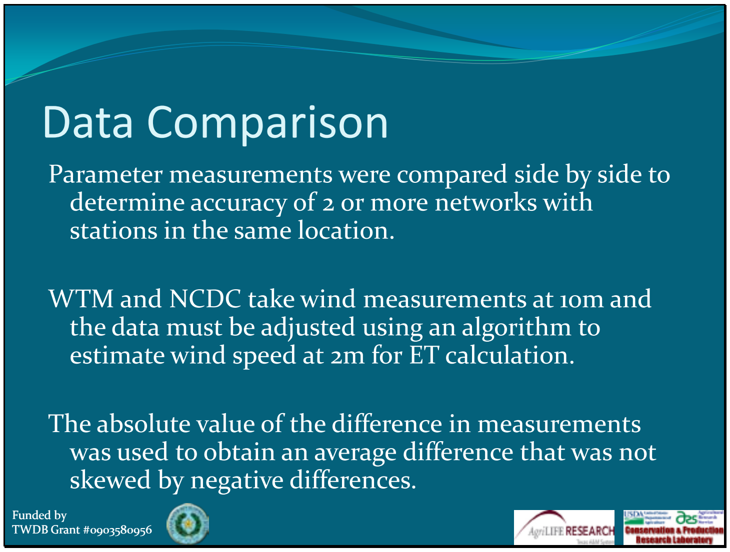

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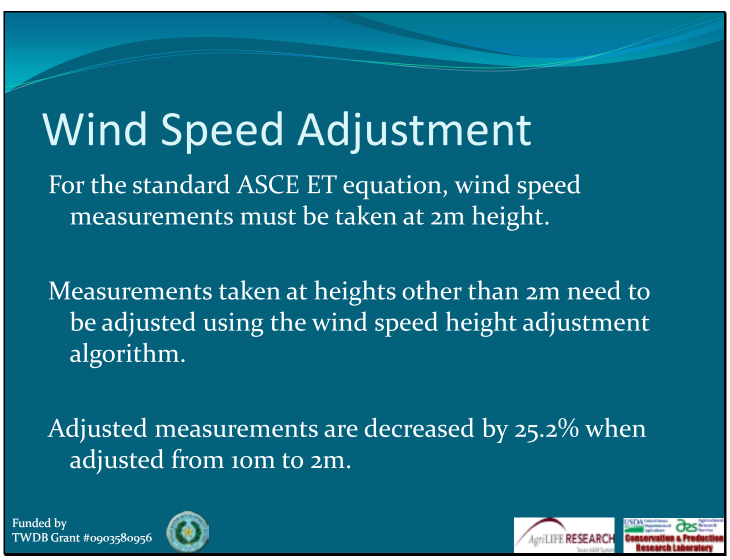

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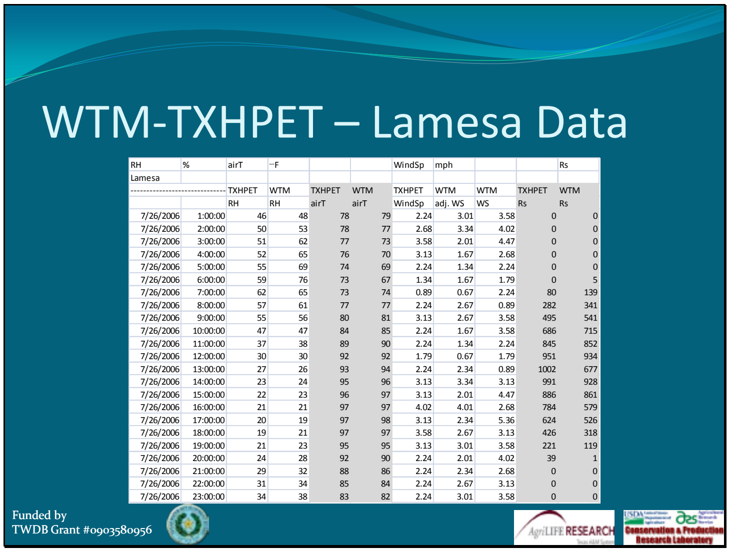
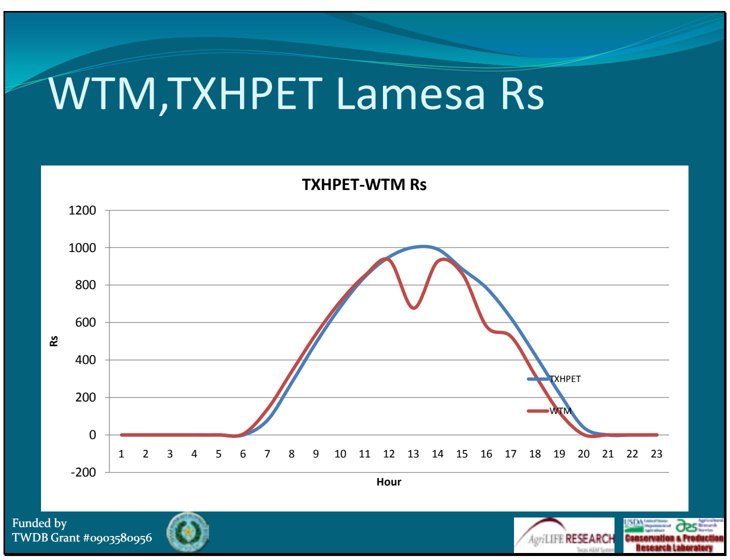
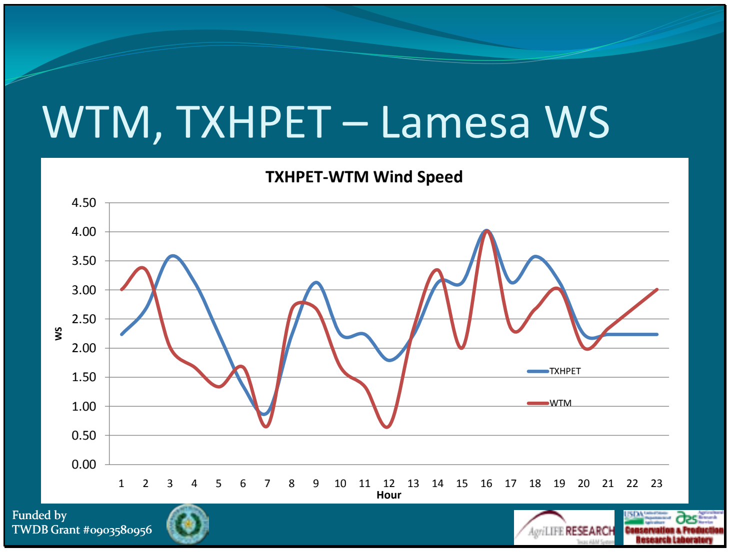


RH	%	airT	~F			WindSp	mph			Rs
Lamesa										
------------------------------		TXHPET	WTM	TXHPET	WTM	TXHPET	WTM	WTM	TXHPET	WTM
		RH	RH	airT	airT	WindSp	adj. WS	WS	Rs	Rs
7/26/2006	1:00:00	46	48	78	79	2.24	3.01	3.58	0	0
7/26/2006	2:00:00	50	53	78	77	2.68	3.34	4.02	0	0
7/26/2006	3:00:00	51	62	77	73	3.58	2.01	4.47	0	0
7/26/2006	4:00:00	52	65	76	70	3.13	1.67	2.68	0	0
7/26/2006	5:00:00	55	69	74	69	2.24	1.34	2.24	0	0
7/26/2006	6:00:00	59	76	73	67	1.34	1.67	1.79	0	5
7/26/2006	7:00:00	62	65	73	74	0.89	0.67	2.24	80	139
7/26/2006	8:00:00	57	61	77	77	2.24	2.67	0.89	282	341
7/26/2006	9:00:00	55	56	80	81	3.13	2.67	3.58	495	541
7/26/2006	10:00:00	47	47	84	85	2.24	1.67	3.58	686	715
7/26/2006	11:00:00	37	38	89	90	2.24	1.34	2.24	845	852
7/26/2006	12:00:00	30	30	92	92	1.79	0.67	1.79	951	934
7/26/2006	13:00:00	27	26	93	94	2.24	2.34	0.89	1002	677
7/26/2006	14:00:00	23	24	95	96	3.13	3.34	3.13	991	928
7/26/2006	15:00:00	22	23	96	97	3.13	2.01	4.47	886	861
7/26/2006	16:00:00	21	21	97	97	4.02	4.01	2.68	784	579
7/26/2006	17:00:00	20	19	97	98	3.13	2.34	5.36	624	526
7/26/2006	18:00:00	19	21	97	97	3.58	2.67	3.13	426	318
7/26/2006	19:00:00	21	23	95	95	3.13	3.01	3.58	221	119
7/26/2006	20:00:00	24	28	92	90	2.24	2.01	4.02	39	1
7/26/2006	21:00:00	29	32	88	86	2.24	2.34	2.68	0	0
7/26/2006	22:00:00	31	34	85	84	2.24	2.67	3.13	0	0
7/26/2006	23:00:00	34	38	83	82	2.24	3.01	3.58	0	0

Slide 230



Slide 231



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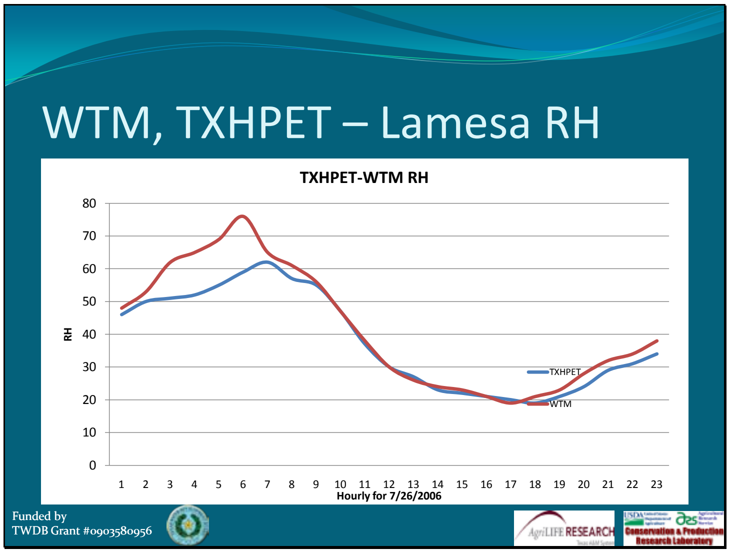

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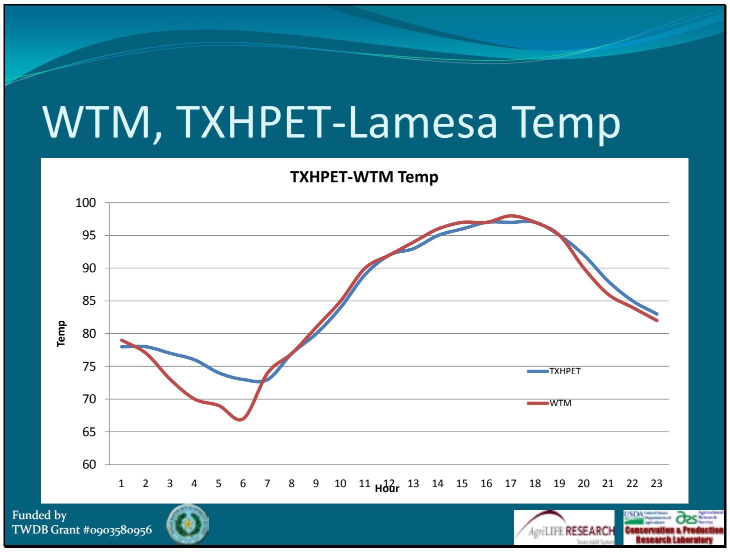

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WTM,TXHPET Lamesa Data

Parameter	Maximum Difference	Minimum Difference	Average Difference
RH (%)	21	0	6.59
Air Temperature (degrees F)	7	0	3.59
Adjusted Wind Speed (m/s)	1.9	.10	.99
Solar Radiation (watts/m^2)	307	5	138.82

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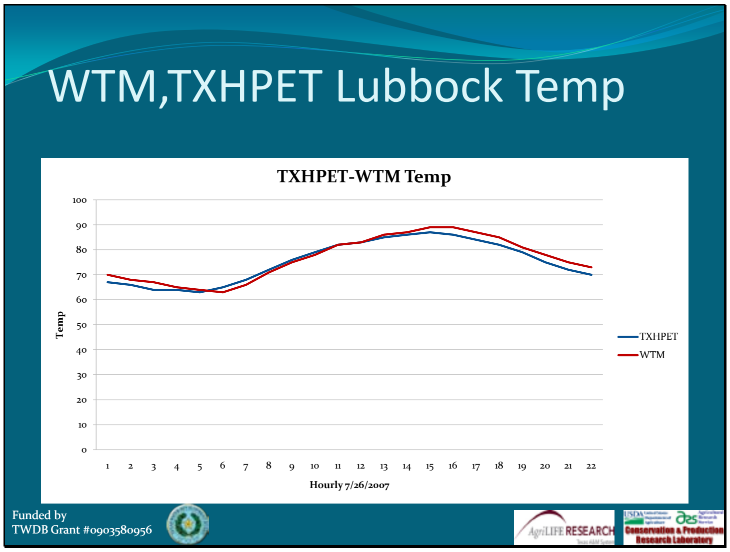
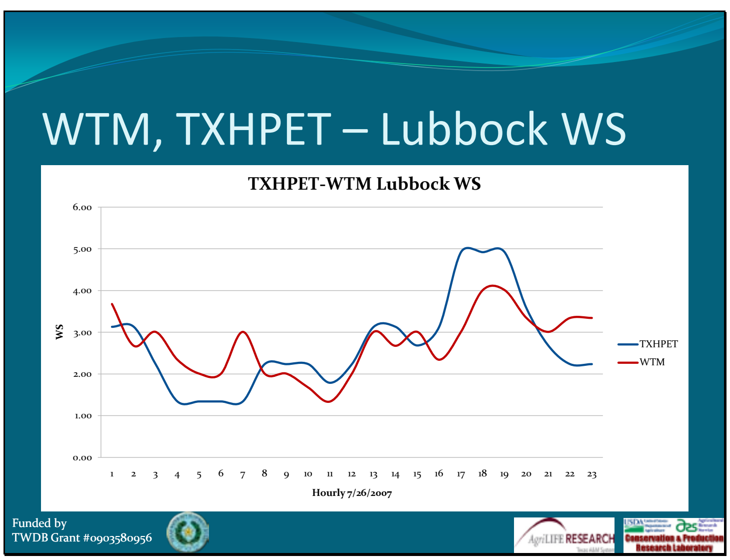


Slide 236



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WTM,TXHPET Lubbock Data

Parameter	Maximum Difference	Minimum Difference	Average Difference
RH (%)	17	0	3.96
Air Temperature (Degrees F)	6	0	1.61
Adjusted Wind Speed (m/s)	1.57	0.01	.62
Solar Radiation (watts/m^2)	325	0	51.57

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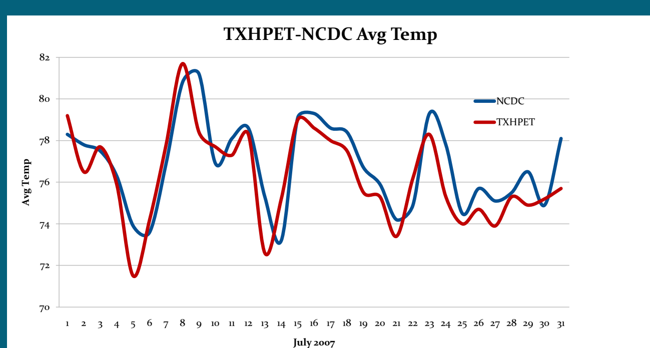
TXHPET,NCDC Lubbock Avg Temp



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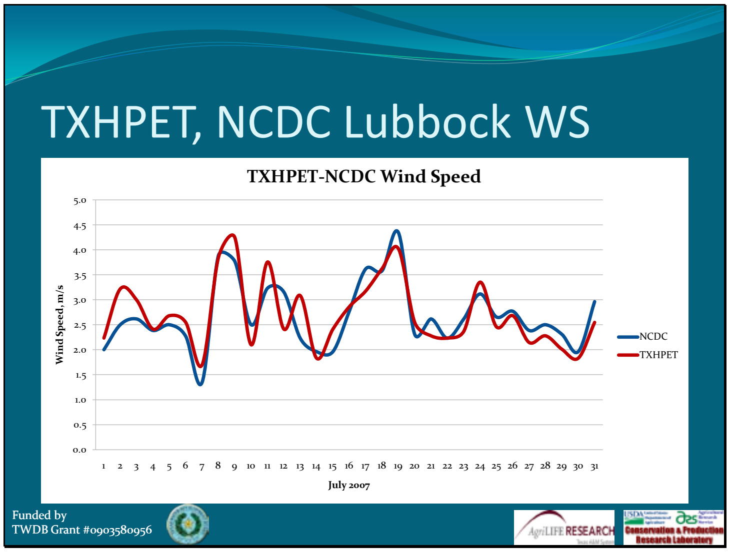

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TXHPET,NCDC Lubbock Data

Parameter	Maximum Difference	Minimum Difference	Average Difference
Avg. Temperature (degrees F)	2.8	0.1	1.09
Max Temperature (degrees F)	10.4	0.1	2.11
Min Temperature (degrees F)	5	0.2	1.49
Dew Point (degrees F)	2.2	0	0.84
Adjusted Wind Speed (m/s)	.85	0	.3
Max Wind Speed (m/s)	11.31	1.48	3.74

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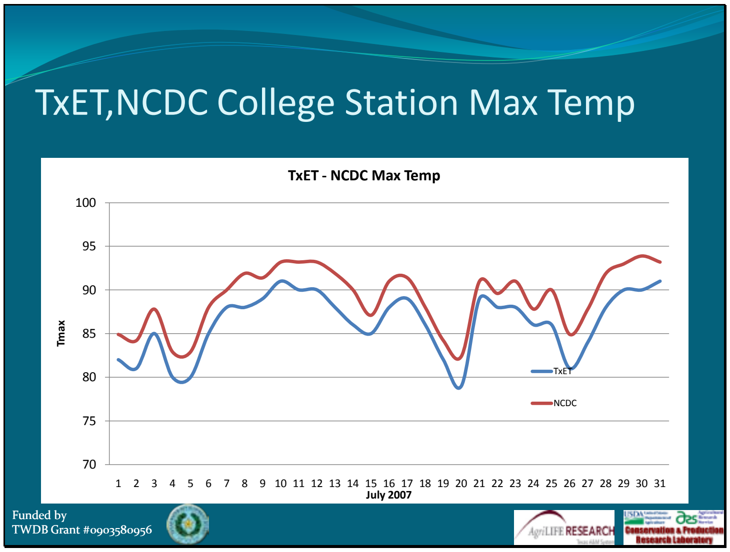

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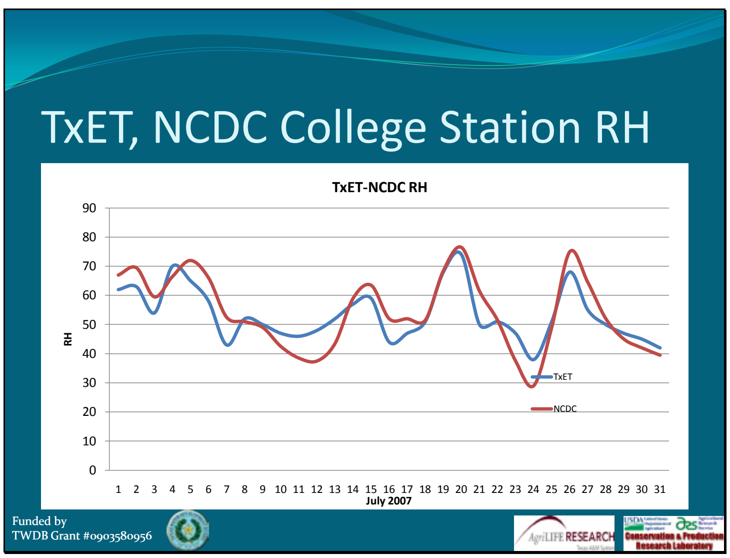
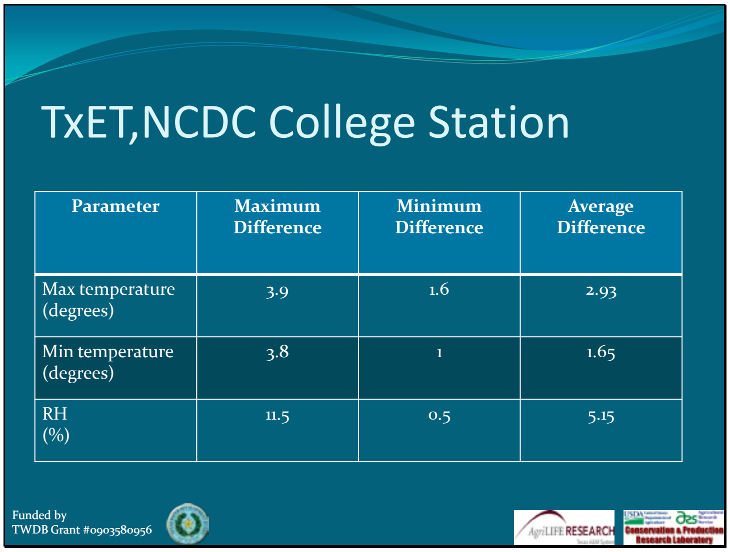


Slide 243



Parameter	Maximum Difference	Minimum Difference	Average Difference
Max temperature (degrees)	3.9	1.6	2.93
Min temperature (degrees)	3.8	1	1.65
RH (%)	11.5	0.5	5.15

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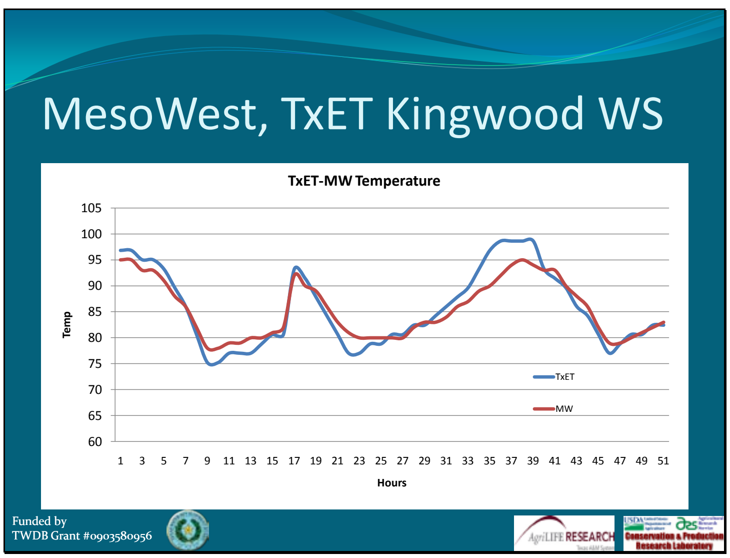

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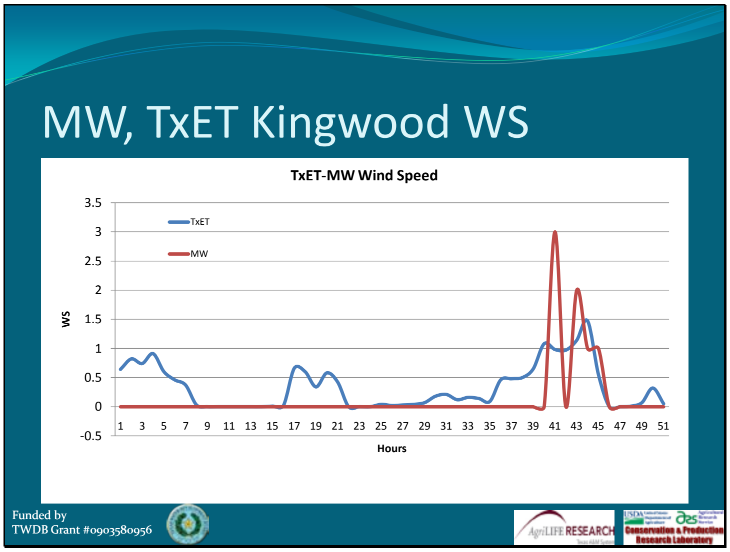

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MesoWest, TxET Kingwood

Parameter	Maximum Difference	Minimum Difference	Average Difference
Temperature (degrees F)	6.8	0	1.9
Wind Speed (m/s)	2.02	0	0.32
RH (%)	20	0	4.7

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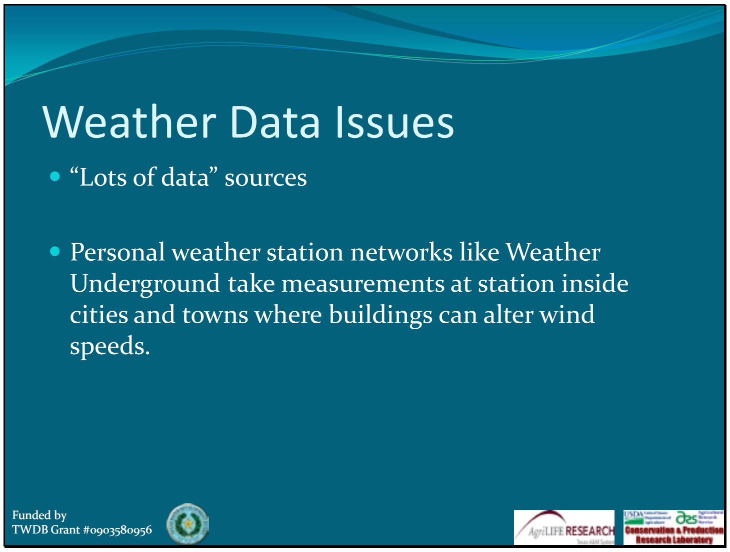
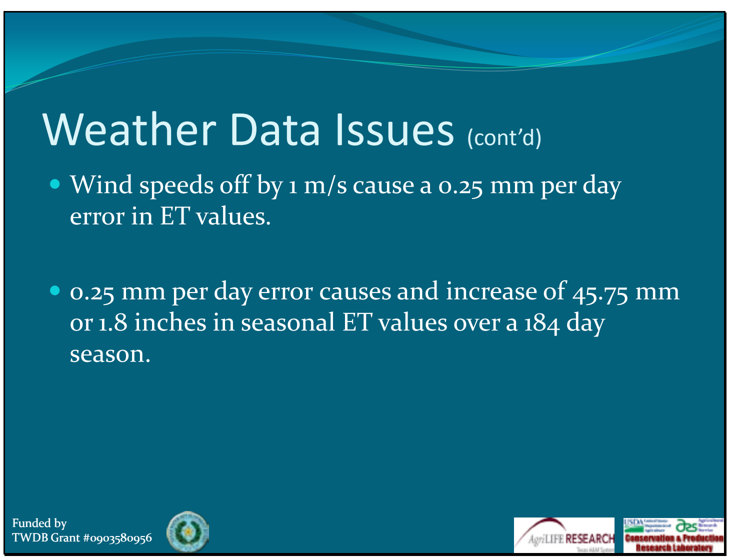
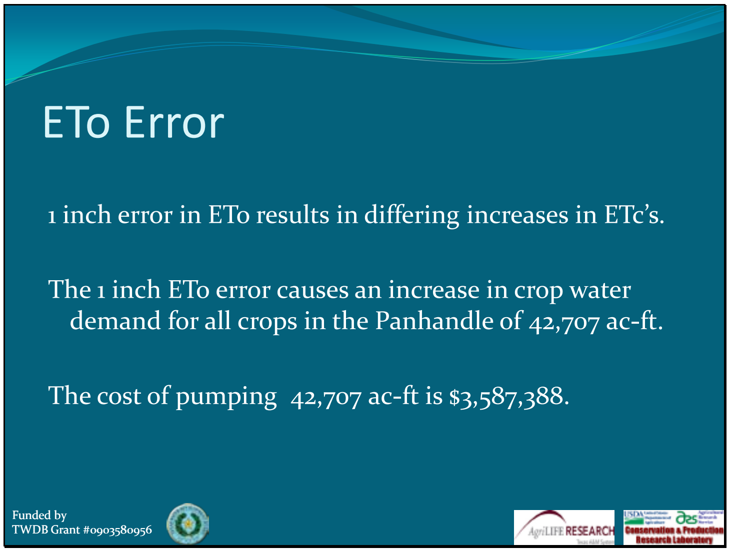


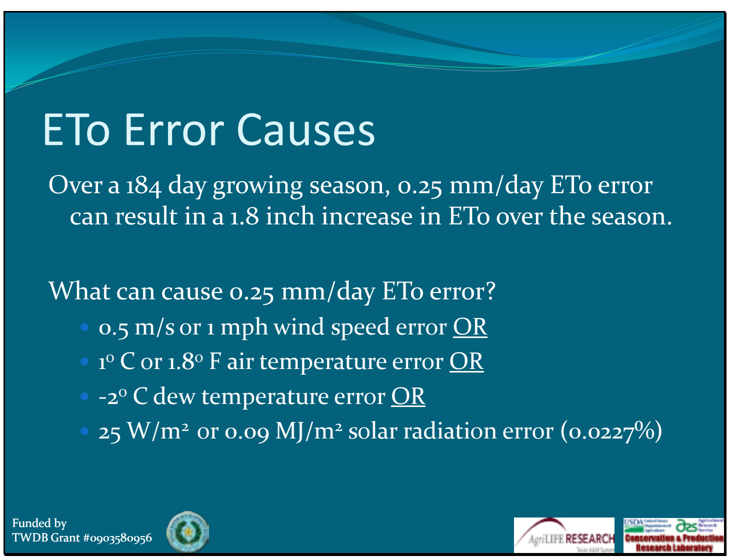
Slide 250



Slide 251



Slide 252



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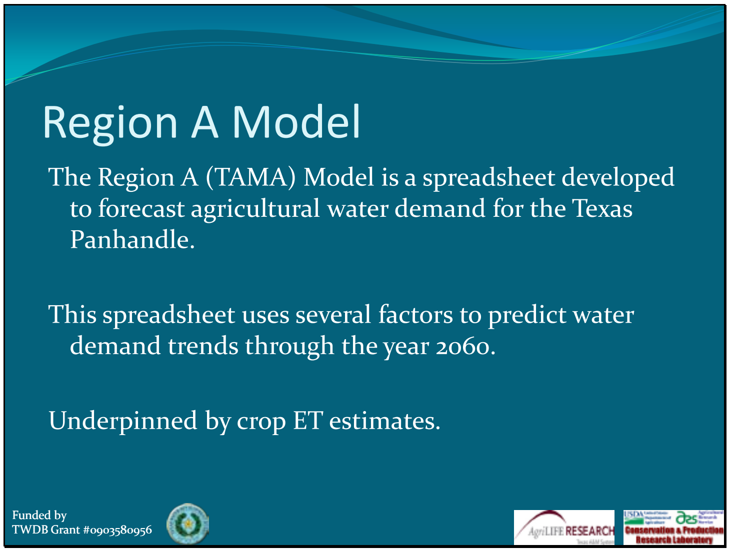
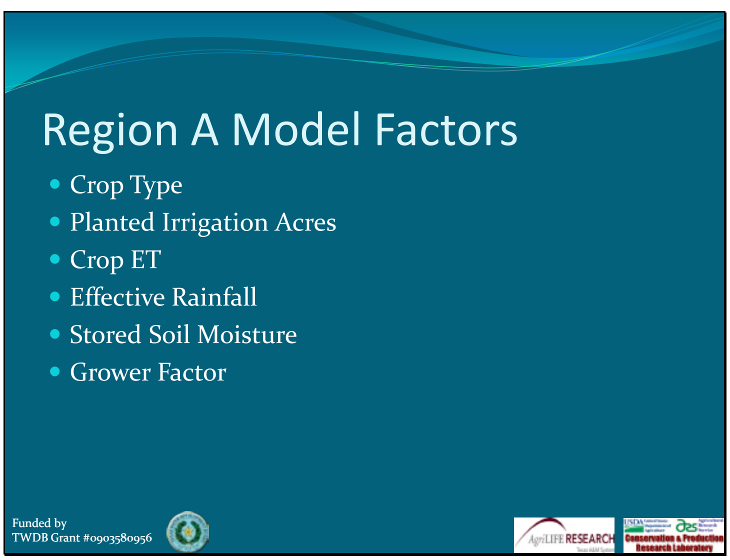
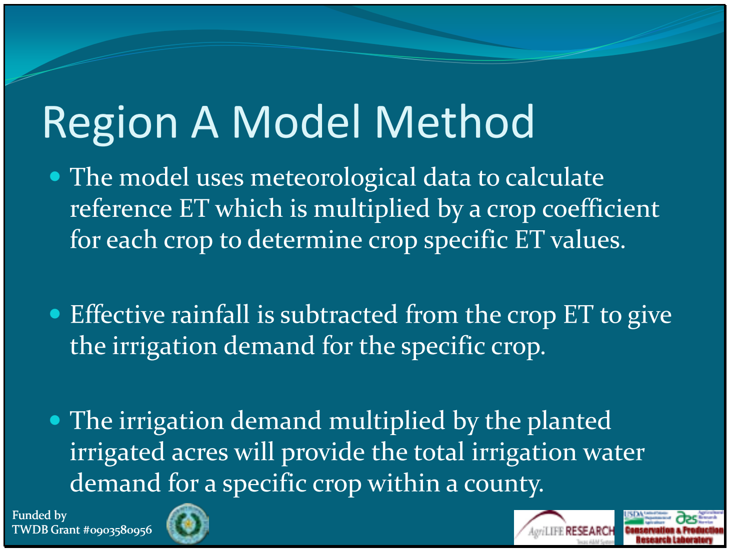


Slide 254



Slide 255



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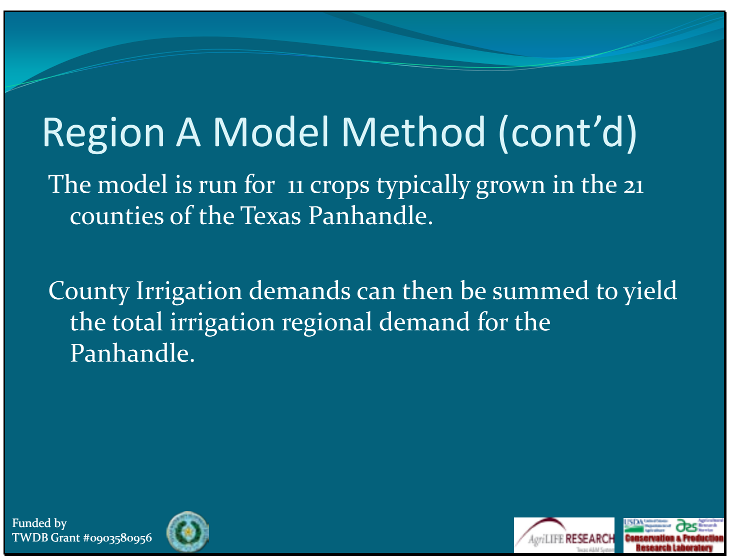

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Region A Counties

- Armstrong
- Carson
- Childress
- Collingsworth
- Dallam
- Donley
- Gray
- Hall
- Hansford
- Hartley
- Hemphill
- Hutchinson
- Lipscomb
- Moore
- Ochiltree
- Oldham
- Potter
- Randall
- Roberts
- Sherman
- Wheeler

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Region A Crops

- Alfalfa
- Corn
- Cotton
- Hay
- Pasture and Other
- Peanuts
- Sorghum
- Sorghum Forage
- Soybeans
- Sunflowers
- Wheat

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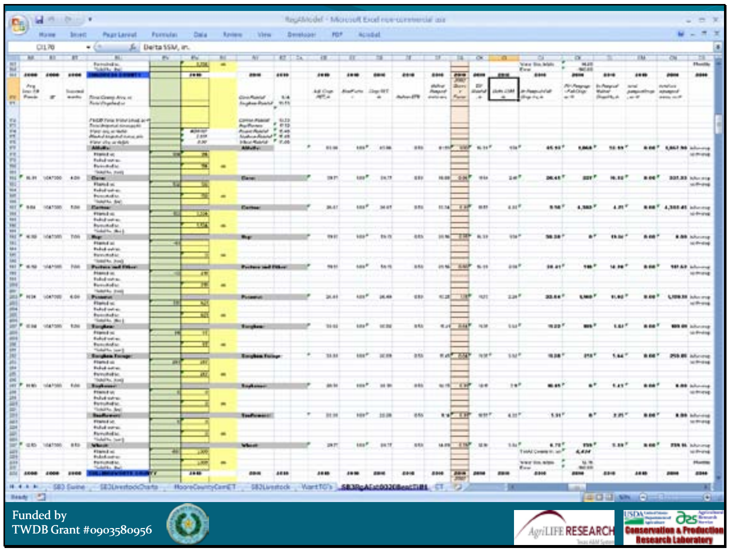
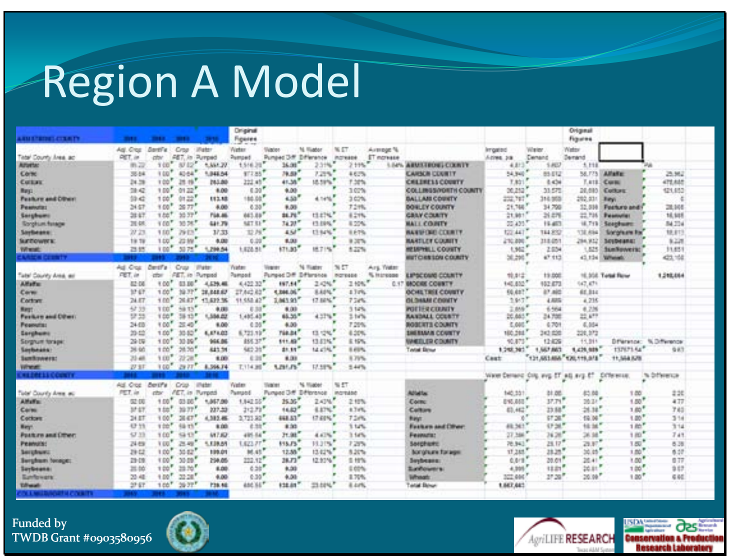


Slide 260



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Growing Season Dates

Crop	Growing Season Used in Crop ET Computations	Season Used in Effective Rainfall (ER) Computations	Number of Months Used in ER Calculations
Corn	April 15 - October 15	April 15- August 15	4
Cotton	May 15-October 15	May 15-October 15	5
Grain Sorghum	May 15-October 15	May 15-October 15	5
Hay	April 1-November 1	April 1-November 1	7
Pasture & Other	April 1-November 1	April 1-November 1	7
Peanuts	May 1-November 1	May 1-November 1	6
Soybeans	June 1-November 1	June 1-November 1	5
Wheat	October 1-July 1	October 1-July 1	9
Alfalfa	April 1-November 1	April 1-November 1	7
Forage Sorghum	May 15-September 15	May 15- September 15	4
Sunflowers	May 15-October 15	May 15-October 15	5

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Corn

The corn growing season is April 15 – October 15.

The season length is 183 days.

Calculations off by only 0.14 mm (or 0.0055 in) will cause an error of 1 inch over the growing season.

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Dallam County Corn

Dallam County irrigates 124,076 acres of corn.

Corn accounts for 53% of irrigated cropland in Dallam County.

This corn crop uses **192,938** acre feet of water.

The irrigation cost of this corn is $16,206,855.

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Dallam County Corn Error

A 1 inch error will increase irrigation to **200,432**, an increase of 7493 ac-ft.

This causes a total cost increase of $629,489.

The error raises irrigation costs by $5.07 per acre.

Irrigation costs rise from $130.62 to $135.69 per acre.

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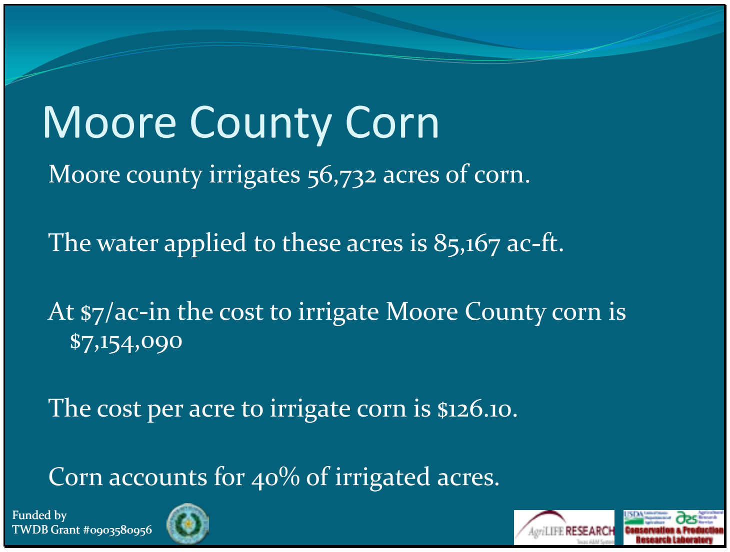

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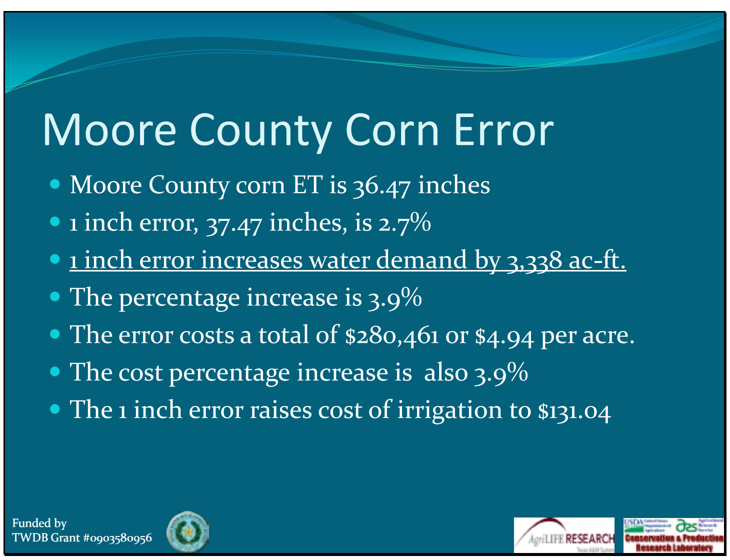

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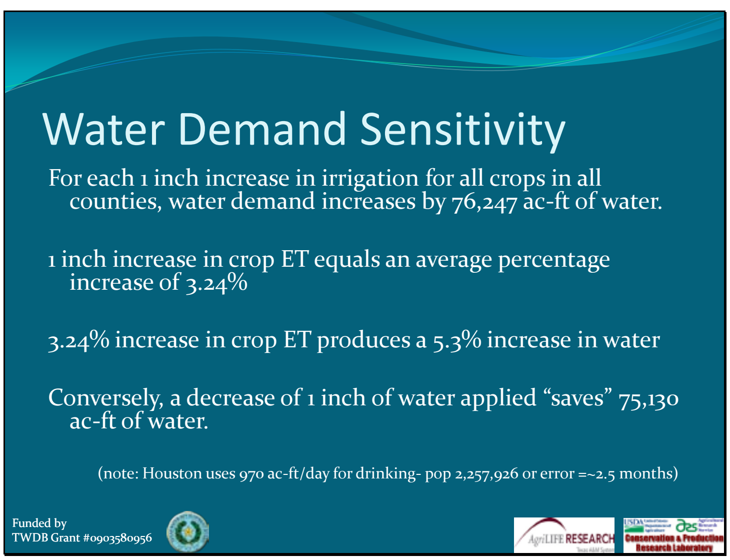
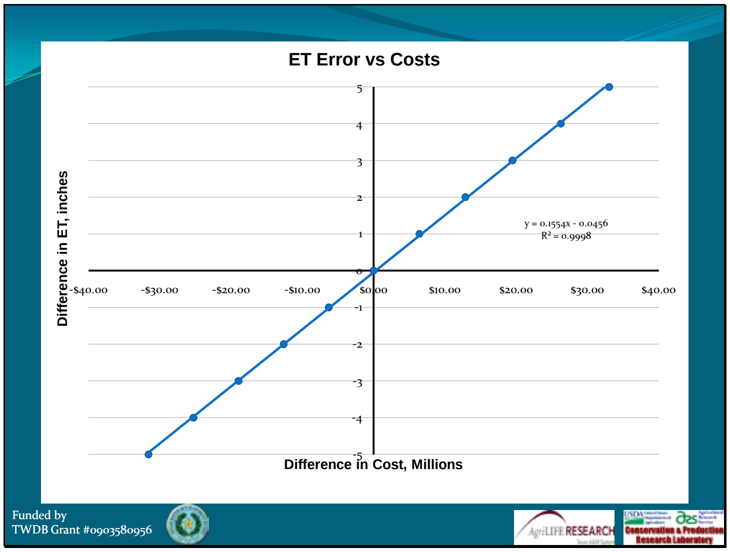
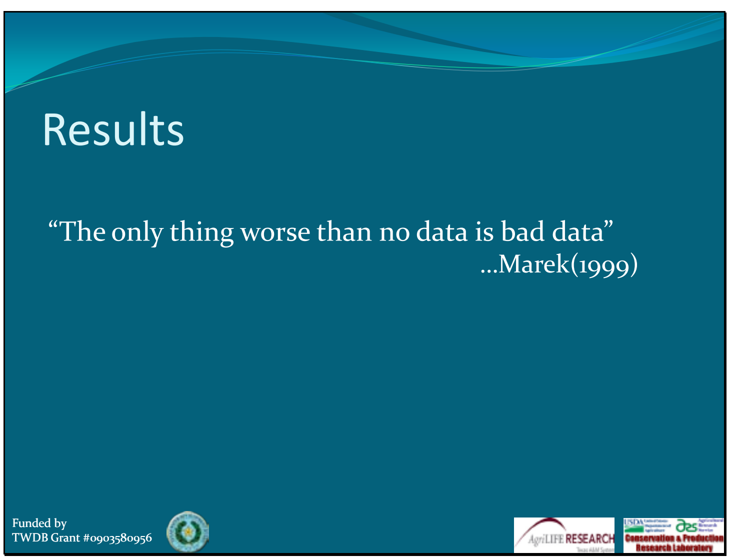
Slide 268



Slide 269



Slide 270



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Results

- 10 networks that record the 4 necessary parameters, 6 networks that record 3 parameters (no Rs), and 8 networks that are not viable for ET calculation.
- QA/QC procedures vary widely, with procedures ranging from completely automated to only visual inspection.
- Errors in parameters cause errors in reference ET. Seemingly small errors in ET equate to large volumes of water in regional water demand models.

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Results (cont'd)

- Sensitivity of the weather parameters varies with the season.
- Absolute errors in reference ET are at least 2 times higher in summer cropping season than the non cropping season.
- SRSM sensors drift differently for each sensor model. No obvious relationship with time and region/climate were found.
- Weather networks with stations in the same location do record differing values. (Different networks use different sensors and at different heights-> Δ values.)

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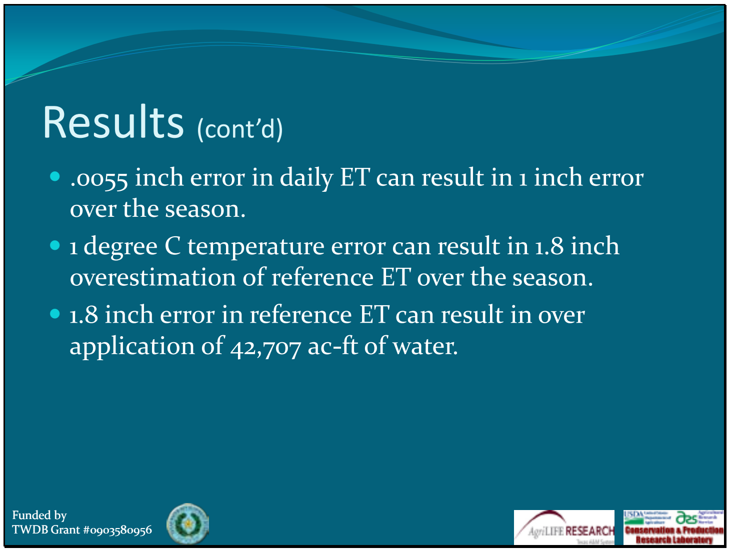
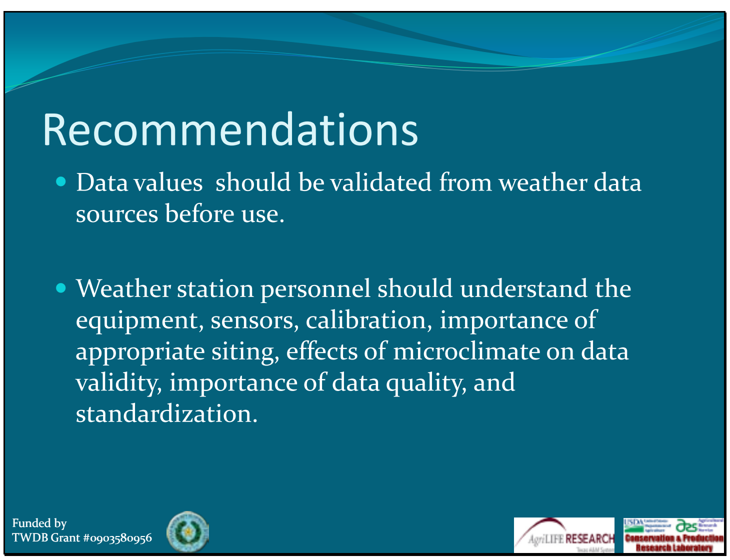


Slide 274



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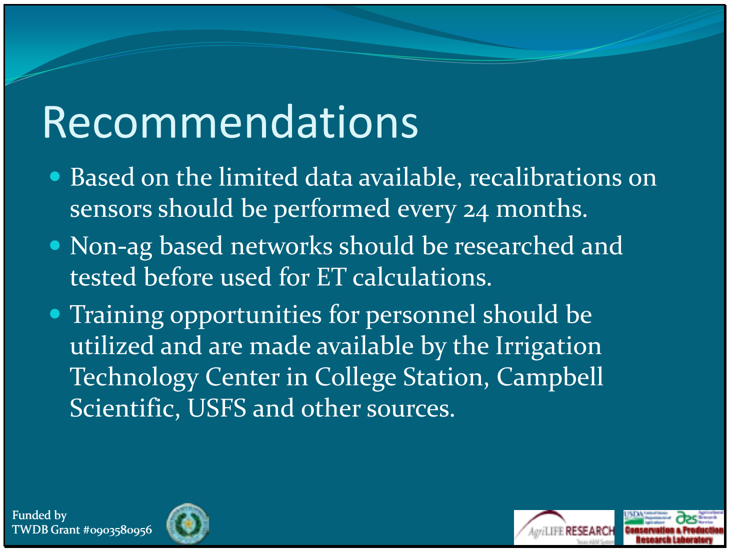
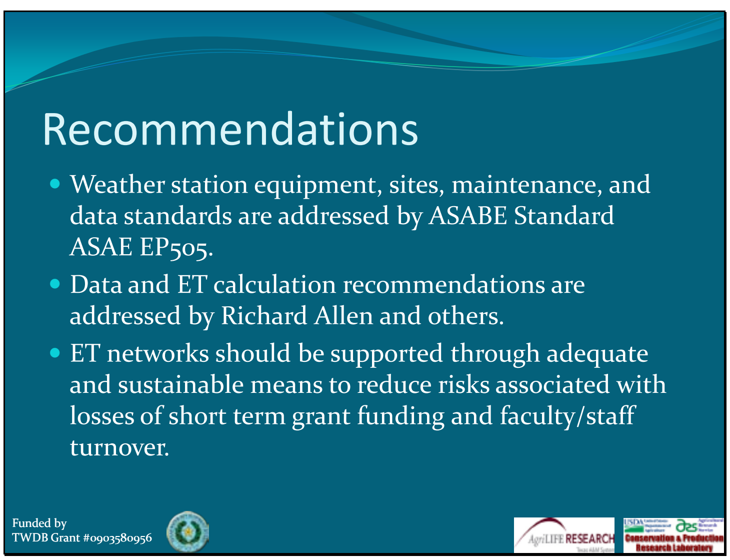


Slide 276



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Recommendations

- Maintain ET estimates on a statewide basis, particularly for irrigated regions. These are necessary for ground-truthing data, regional water planning and district-level water resources allocation (permitting) as well as for farm-level irrigation planning and management.
- Establish statewide ET data and provide funding necessary to support infrastructure and staffing needed to ensure data integrity.
- ET calculations, siting, and QA/QC should comply with ASCE EWRI and ASABE standards.

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Questions or Comments?

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Appendix F – Attachment I – TWDB comments on initially prepared project report

The project team appreciates the initial report review and comments/questions forwarded by the project manager. Each of the items was addressed as defined below and changes/additions have improved and clarified aspects of the project report. (Page numbers immediately after the item refer to pages in the draft version. Page numbers in the responses are in reference to this final version of report).

Item 1. Cover – Please put the correct contract number on the cover.

Response: TWDB contract number was corrected.

Item 2. Page 2, second paragraph – Add TWDB RWPG map for visual reference.

Response: The map was inserted on page 4.

Item 3. Page 16 – Question to consider adding: "Does any ET network plan/use the ASCE recommended ET computational method?"

Response: Statement was added listing Texas networks that explicitly utilize reference ET by the new ASCE standardized equation (page 17).

Item 4. Page 17, Last sentence – Revise to state that TXHPET network is no longer available to the public.

Response: Statements were added to reflect the current status of the TXHPET network at the end of the TXHPET section (page 21).

Item 5. Page 70 – Please delete the sentence that reads "The project PI's hope that these type conflicts can be resolved…".

Response: The statement was deleted.

Item 6. Page 77 – Please provide a Task 2 Summary section that includes the alternate acquisition methods that were implemented due to travel restraints.

Response: A summary section on minimum QA/QC was inserted at the end of Task 2. The summary included the last paragraph of the results section. The alternative methods used for the task were inserted before the results section on page 72.

Item 7. Page 92 – is it possible to analyze the solar sensor degradation data for ET stations located in Texas?

Response: The solar radiation sensor data were analyzed for sensors located in Texas and the analysis was added to the end of the results section for Task 5 (pages 101-103).

Item 8. Page 119 – Please add information found from revised methods in Task 2.

Response: A task summary was added at end of Task 5 as it relates to the sensitivity values determined and the sensor accuracies.

Item 9. Pages 121-123 – Can this model/application/spreadsheet be shared with TWDB staff? And/or presented in more detail in the final report?

Response: The TAMA model is not available for distribution. A brief section on details of the model was added within the section. The model terms were updated in the Glossary of Terms and Abbreviations.

Item 10. Page 127 – Add a table listing the categories of networks, their names/acronyms, and a summary of which are suitable for our use in calculating ET estimates.

Response: The table was added to the Project Conclusions section of the report.

Item 11. Page 129 – Some specific mention should be made as to the discontinuation/unavailability of the AgriLife High Plains ET stations data. Reasons for why they were taken offline and the availability of data in the future needs to be addressed in this report. This represents a HUGE gap in the ET networks analysis as these were the most reputable/trustworthy available source of ET data. Where do we go, what now?

Response: A discussion of the above issue was added on pages 141-142.

Item 12. Page 133 – Typo: "…established to be a 10,000 year old resource and is heavily…"

Response: The typo was corrected.

This report may be referenced as follows:

Marek, Thomas H., Dana O. Porter, Prasanna Gowda, Terry A. Howell and Jerry E. Moorhead. 2010. Assessment of Texas Evapotranspiration (ET) Networks. Technical Report for Contract #0903580904 to the Texas Water Development Board, Austin, Texas. Texas AgriLife Research, Amarillo, Texas. AREC publication 201011-12. 379p.