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QUALITY CONTROL OF DATA FROM THE US CLIMATE REFERENCE NETWORK

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1. INTRODUCTION

The primary goal of the USCRN is to significantly reduce the uncertainty in the current long term measurements of temperature and precipitation through the use of accurate and redundant sensors. (USCRN FRD 2003). The uncertainty in the current climate record is a result of compromised measurements for a number of different reasons. Some of these are: change in station location, change in albedo or land use near the station, change in instrumentation, change in the time or frequency of observations, change in observer, and last but not least, inadequate maintenance.

More than 40 years ago Dr. J. Murray Mitchell of the Office of Climatology USWB sought to answer many of the above mentioned uncertainties. From the existing USWB Cooperative Observer Network he selected about 30 stations that had well-trained observers and apparent temporal and spatial stability (personal communication, W. Haggard 2003). These sites became known as Reference Climate Stations (RCS). After the untimely death of Dr. Mitchell, interest in and funding of the RCS decreased to the point where instruments at some sites failed while others sites had significant compromises of their immediate surroundings. The program was terminated in the late 1980's.

Currently the USCRN is actively addressing all of the aforementioned areas of data compromise beginning with a rigorous site selection process and ending with a near real time human/machine quality assurance of meteorological data and sensor performance. This paper will center on the quality assurance of the data while at the same time touching on the reasoning behind the design of the observing system. Continued support and adequate funding to maintain a standard for equipment calibration, maintenance, and data quality assurance are necessary so that the future of the USCRN does not mirror that of the RCS.

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2. GENERAL OVERVIEW OF USCRN QUALITY CONTROL (QC)

One of the greatest strengths of the USCRN quality control (QC) program is the near real time mode of data review. The hourly receipt of the data through the GOES Data Collection System at Wallops Island, VA, allows the QC review of the automatic QC flags assigned by NCDC algorithms and comparison of the flagged observations to other data (radar, satellite, mesonets, or web-cams) to assess instrument performance and data validity. Such timely review would not be possible without the internet access of these corroborating sources.

Most of the current QC flag limits are set at a level to cover the expected extremes for the Nation as a whole; however, these limits will be adjusted to the climate of each station in the near future. Presently data are accumulated from each site and will aid in developing these more appropriate limits. Limits for temperature and precipitation can be inferred from nearby existing climate stations. However, setting expected limits for other sensors such as wind speed, will require some additional effort since the reported speeds from USCRN are hourly averages as compared to the two minute averages of today's ASOS or the one minute averages of the pre-ASOS period. Those observations were also recorded from anemometers that were exposed 6 to 10 meters above ground as opposed to the 1.5 meter height for USCRN. Limits are also used for the reported values from other supporting meteorological sensors such as infra-red (skin) temperature and solar radiation.

Unlike many other meteorological networks, the USCRN stations also report non-meteorological data that assist in assessing the performance of the meteorological sensors and the data they report. Probably the most important of these is the rate of rotation of each aspirating fan located in the top of each of the three temperature shields. Experience has shown that any rate less than about 80% of

normal begins to compromise the temperature readings from that shield. Therefore, any time the rate drops below that level a flag is appended to the temperature observation in the database and a message is sent to the QC staff who assess the nature of the excursion before entering it into the Anomoly Tracking System (ATS). The ATS reports provide a basis for the investigation and solution of the problem by the engineering staff at the Atmospheric Turbulence Diffusion Division (ATDD - Oak Ridge, TN).

3. AMBIENT TEMPERATURE

During the first year that USCRN stations were deployed a robust type of thermister was used for the sensing of ambient temperature; however, during this period those sensors failed to meet the USCRN accuracy requirements of 0.1° C and the related allowable absolute difference standard of 0.3° C among the three separately aspirated temperature readings (USCRN FRD). Therefore, the initially chosen thermisters were replaced by more accurate and stable platinum resistance thermometers (PRT) which have demonstrated excellent performance over the last 12 months and are traceable to National Institute of Standards and Technology calibration. A statistical analysis of the PRTs across the USCRN for the last year shows the following results with regard to their comparative stability (See Table 1):

TABLE 1: Percent Of Hourly Observations For Various Levels Of Absolute Temperature Differences Between All Three Sensors.

<=0.05 C	58%
<=0.10 C	86%
<=0.20 C	97%
<=0.30 C	98%

Even with the best of equipment there will always be some failures or compromised performance, and that is why the USCRN chose to use three separate aspirated shields each of which contains one PRT. Upon those infrequent occurrences when a sensed temperature difference falls out of the 0.3° C comparative tolerance for more than three hours in a row, the QC staff examines all other relevant data to determine if it is meteorologically driven or perhaps failure of the PRT or its aspiration. This examination starts with a check of the rotation rate of the aspirator fan of the affected shield and temperature sensor. If the aspiration rate of the fan is nominal, then the PRT is examined to see if there was a recent drift within the 0.3° C tolerance window prior to its first exceedence. Scrutiny of a flagged PRT usually continues through at least one daylight period to see what, if any, effects solar radiation and the wind have on the readings. If the reported temperatures continue out of limits after this period an ATS report is generated for review by the engineering staff. A permanent record of the ATS is maintained as well as the data quality flags in the database. It should be emphasized that the original data and its associated flags will be preserved even if reprocessing occurs with additional or refined algorithms.

In those cases where the errant temperature readings result from an inadequate aspiration by the fan, it is frequently detectable through the elevated temperatures in the affected shield (See Figure. 1). If not detected through this method (due to night time or cloudy conditions) then certainly it will be reviewed because of the zero fan speed in shield #1. These warmed readings are particularly obvious during sunny days with light winds. It is interesting that Figure 1 also shows that even after sunset, the temperature readings from sensor #1 (gray to green line in Figure 1) fall back within the 0.3° C limit but are still warmer than the readings of the other two sensors. This indicates that, even with no sunlight and considerable ventilation by the ambient wind flow (4+ mps in this case), there is still a detectable warm bias in the temperature readings from the non-aspirated shield. The temperature readings in shield #1 returned to perfect agreement with the other two when the inoperative fan was replaced.

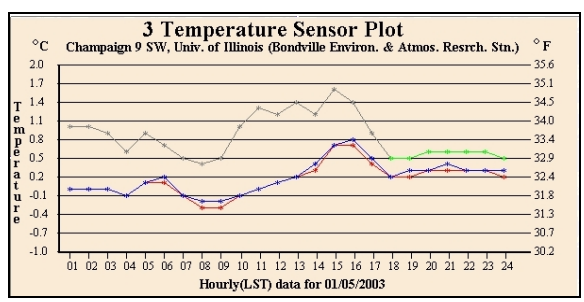

Figure 1. Ambient temperatures for Champaign 9SW , IL

So far most of the episodes of compromised aspiration have resulted from a loss of electrical current to the fan as opposed to a failure of the fan motor itself. Certainly the net effect to the temperature sensor is the same, however, the solution was different. So far there has been only one fan failure in the more than two years of the USCRN. However, there have been several occurrences of aspiration

compromise due to a slowed or zeroed fan speed because of a reduction or loss of electrical current to the fan motor. ATDD engineers identified that this problem was caused by the corrosion of the power terminals on the fan. These steel terminals have since been replaced with gold plated ones that do not corrode. There have been no repeats of this problem since the conversion.

There was one unusual case where one fan was reporting no rotation during a daylight period with considerable solar radiation and low wind speeds and yet the reported temperatures from the PRT in the affected shield were in line with the readings of the other two PRT's. The source of this problem was that the wire connection from the rotational counter of the fan to the data logger had been compromised. It was falsely reporting that the fan was not turning while in reality it was running at a nominal rate.

Earlier in this section it was mentioned that no immediate human action is taken when a PRT exceeds the 0.3° C difference limit for less than 3 consecutive hours. The reason for this allowance comes from observation of numerous events that have occurred at almost all network sites and during most months of the year. In these cases one or two of the PRTs will read temperatures that are greater than 0.3° C from each other for one to three consecutive hours. This despite the fact that the shields are only about one meter from each other (See Figure 2) and the compared temperatures are an hourly average. At first it was believed that there might be a problem with the PRT sensors. The PRTs at the two Asheville, NC sites were examined for any contamination that might cause a differential ventilation of the sensors or evaporation of moisture from those same sensors during their transition from a saturated to non-saturated airmass. The examination found no such significant differences in contaminates. The vast majority of these excursions in the temperature readings only last for one hour, but may involve one, two, or all three temperature sensors. The most frequent time of occurrence is the first hour or two after sunrise when there is a large change in solar forcing as well as calm to light winds. The magnitude of the temperature differences are usually between 0.31° and 0.8° C.

4. PRECIPITATION

Most global atmospheric models that predict a warming of the overall atmosphere also predict a shift in regional precipitation patterns as well as changes in the intensity of the precipitation (National Assessment Synthesis Team, 2000). Therefore, it was incumbent upon the USCRN to employ the use

Figure 2. Aspirated Shields each containing one PRT

of a gage that would function and accurately record the measurement of precipitation at any intensity. It also had to be able to accurately measure solid precipitation since a significant amount of precipitation in many parts of the US falls in solid form. These measurements must be accurate for both the total amount and intensity of each precipitation event if the science community is to understand and account for current and future ambiguities in the precipitation records.

After considerable investigation and research the USCRN decided upon the GEONOR, a mass weight gage similar to the "Universal" Weighing Precipitation Gage that had been the official gage of the National Weather Service from the early 1960's to the mid 1990's. At that time they were replaced by the Automated Surface Observing System's (ASOS) heated tipping bucket precipitation gage (Goodge, 2003). The major difference between the Universal gage and the GEONOR is the method in which the amount or mass in the receiving bucket is determined by measuring the change in the vibrating frequency of a wire or wires that support the mass of the bucket and its contents. The Universal gage used a spring loaded scale (similar to a grocery store scale) to sense the mass. Both the Universal and the GEONOR gages are accurate to 0.25 mm (.01 in) which has been the standard resolution for the measurement of liquid precipitation in the U.S. weather services. The common configuration of the GEONOR gage is to have only one wire and two chains that support the bucket and its contents (Bakkehoi 1985). However, with the vision that the USCRN was the new baseline of climate data its precipitation measurements could not be placed at risk with that one wire being a single point of failure. Despite its excellent performance in the Scandinavian weather services over the past fifteen years there had been several occurrences when the sensing wire had

broken. Therefore, it was decided to install three wires and their attending transducers on all GEONOR gages in the USCRN.

What was not known to the USCRN program at the time was that if one wire broke in the three- wire configuration it severely compromised the measurements from the two remaining wires due to a significant shift of the bucket from horizontal. Fortunately ATDD engineers designed and tooled a safety collar that is attached to the bottom of each of the three transducers. This keeps the bucket sufficiently level so the remaining unbroken wires are able to continue the accurate reporting of precipitation. The most likely meteorological cause of a broken wire(s) would be large hail falling directly into the bucket. This would be particularly true at times when there was a minimal amount of liquid in the bucket.

Recognizing the inherent problems in the accurate measurement of snowfall, the GEONOR has been retrofitted with thermostatically controlled heat tape on both the top and bottom portions of the receiving chute of the gage. This prevents the "bridging" of the rim and inside surfaces of the gage by wet snow. The other major problem of accurate precipitation measurements is related to wind. This is particularly true in the measurement of snow. Research indicates that under catch of snow can be as great as 75% in winds of only 15 mph at gauge height.(Goodison, 1978). Therefore, the USCRN uses three separate wind shields to surround the GEONOR gage. The first wind shield is called an "Alter" and surrounds the opening of the GEONOR at a distance of 0.6 meters. It has a series of metal leafs that pivot on the shield's supporting ring. Further out from the GEONOR gage and the Alter shield, there are two additional wind shields in the form of wooden snow fences. They surround the gage at distances of 1.7 and 4.0 meters (See Figure 3). The fences are not solid but rather slatted to allow some wind to pass through at a much slower speed. A solid barrier would cause the wind and snow to go up and over or around the fence as well as the precipitation gage. Studies have shown that this configuration of wind shields improves the catch to about 96% of true catch (NCAR, 2001).

Despite the triple redundancy of the three separate wire sensors on the GEONOR precipitation gage, there was concern that an extended precipitation event, tropical or orographic, might exceed the 600 mm (24 inch) capacity of the GEONOR's receiving bucket. Therefore a second precipitation gage, of the tipping bucket design, was installed at those sites most likely to experience such large precipitation events. The remaining stations will have the secondary precipitation gages installed at

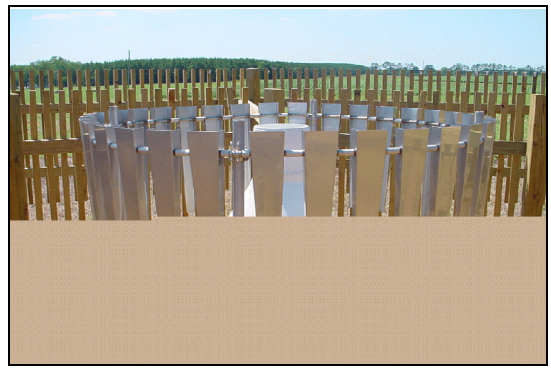

Figure 3. Wooden Snow Fence

the time of the next annual inspection. Those stations that are located where snow is common will be equipped with heaters. These secondary gages will be installed inside the two snow fences but not inside the Alter shield.

The potential inaccuracies of measurements by a tipping bucket in intense short duration rain events was known. However, it was believed that the network needed the redundant capability of a gage that has no limitation on the amount of total rainfall it can measure. As for the problem of inaccuracies in high rain rates, the selected tipping bucket gage (Echo Harmony TB3) employs a siphon that delivers a constant flow velocity to the tipping bucket at rainfall rates up to 500 mm/hr (ECO Harmony 2001). The tipping sensitivity is 0.2 mm which is slightly less than 0.01 inches. These gages were installed at seven of the southeastern sites in July and August of 2003. Based on the results from numerous rainfall events the measured amounts have compared very favorably with the co-located primary GEONOR gage.

Current automated QC checks are set to the sensor range limits of the GEONOR. They are 0 to 600 mm for gage depth in the bucket, 0 to 600 mm for the data logger derived 15 minute precipitation amounts, and 1000 to 3000 hz for the vibrating frequency of the wires. All intensity and duration checks for both gages are manual at this time. However, with the multiple wire sensors reporting three independent precipitation values from the GEONOR there is more data available to detect a problem. The addition of the TB3 now allows a true collocated comparison against all three values reported by the GEONOR. As was noted above, the comparison of values between the two gages for many precipitation events has been very good. There have been some cases where there are differences between the two gages, but the vast majority of those are when the TB3 reported no precipitation while the GEONOR did. Due to the original short sampling time for the frequency of the vibrating wires on the GEONOR, it was occasionally reporting small

amounts of precipitation during a 15 minute period. These small amounts were usually 0.1 to 0.3 mm. However, when summed for the day the total can amount to what may appear as a real precipitation event. This accumulation of "noise" has been addressed by increasing the sampling period of the vibrating wires by the data logger program.

As was earlier mentioned, the manual review of the hourly USCRN involves the use of all known available data from radar, satellite, mesonets, or other nearby meteorological networks. Even web-cams can be extremely useful in determining the conditions during a questionable event. The origin of some of these questionable precipitation reports occurs when a cooperating site host recharges the GEONOR precipitation bucket with oil or anti-freeze without notification. Other questionable precipitation reports have involved the time distribution of the precipitation rather than the amount. Several of these events occurred last winter in the form of freezing rain at several sites that had not yet been equipped with the heat tape on the GEONOR's chute. The total precipitation was accurate but not its time of occurrence. The ice melted into the bucket the day after the event when the temperature of the chute rose above freezing. Future plans are to add a temperature sensor that will monitor the performance of the heat tape as it applies sufficient heat to the sides of the chute to keep it clear of ice and snow.

5. SOLAR RADIATION DATA

One of the other goals of the USCRN program is to establish a relationship (transfer function) between the temperature data at a USCRN site and the measurements of other nearby climate stations. If the terrestrial exposures of the two sites are similar, then solar radiation will likely produce the greatest difference in the reported temperatures. Most of the current and past temperature records have been recorded in un-aspirated shelters that absorb some of the sun's energy even though the shelter is painted the required reflective color of white. Some of that energy is transferred into the shelter and produces a warm bias when compared to the USCRN temperatures, particularly on days when the wind is calm. In contrast, all USCRN sites have their temperature sensors located inside a shield that has not one but three layers. The two interior layers of the shield are ventilated by the fan as well as the PRT that is located inside the third layer of the shield. The fan generates approximately a 5 mps rate of flow past the PRT. Understanding the measurement differences between the USCRN and other climate stations would be difficult without the solar radiation measurements.

The current automated solar radiation QC limits are again global in nature, but will be refined to fit each station by time of day. These tailored limits will be developed from the "clear sky" model. So far only one solar radiation value has significantly exceeded the predicted level for the latitude and time of year. The apparent excessive reading was recorded at the site near Elgin, AZ, when a frontal band of clouds passed over the station during the early afternoon and produced about 150 watts/square meter of back scattered radiation. The high solar radiation value was confirmed by a collocated surface radiation (SURFRAD) solar radiation sensor. The presence of the cloud bank was visually confirmed by archived photos from the SURFRAD web cam.

6. INFRA-RED SURFACE (SKIN) TEMPERATURE

As was discussed above, direct solar radiation warms the surface of any object exposed to the sun. However, the sun does not directly heat the atmosphere. Rather it heats the ground or any objects near the ground (skin temperature) which in turn re-radiate that heat into the atmosphere and warms the air. Therefore, it is important to know the temperature of the ground/vegetative cover beneath the air temperature sensors to assess the magnitude of the heat flux between the ground and the air 1.5 meters above where the ambient temperature is measured. For any given amount of solar radiation the type of ground cover and its color will greatly affect the temperature of that surface and in turn the temperature of the air above. Dark colored surfaces absorb more heat than light colored surfaces, and bare soil or dead vegetation will absorb more heat than living vegetation. This is one of the reasons that the USCRN program requires the engineers or technicians to take photos of the ground cover at the site and its surroundings at the time of installation and each annual station visit. The type of ground cover near the site also affects the amount and rate of heat loss back into space on a clear night. These "skin" temperatures not only aid in developing the transfer functions between the USCRN stations and other pre-existing stations, but they also aid in checking the validity of the infra-red sensor values by comparison with the three ambient temperature sensors. If skies are clear during the day, the infra-red temperatures will be significantly warmer than the ambient temperatures, and if the remain clear during the night, the infra-red temperatures will usually be equal to or slightly colder than the ambient temperature. There are, however, occasions when this relationship is not

true. One is when the ground is covered with standing water from heavy rains. Given that water has a greater specific heat than soil or grass, the infra-red temperatures were warmer during the night and cooler during the day. Snow cover creates an even more interesting relationship between the ambient temperature and the infra-red. If the ground is covered with snow, the infra-red temperatures will not rise above 0° C regardless of how far the ambient temperatures rise above 0° C (See Figure 4). As is shown, the ambient temperatures rose to nearly + 5° C during the midday hours while the infra-red temperatures stopped increasing near the freezing mark at 10:00 LST and remained unchanged the rest of the day.

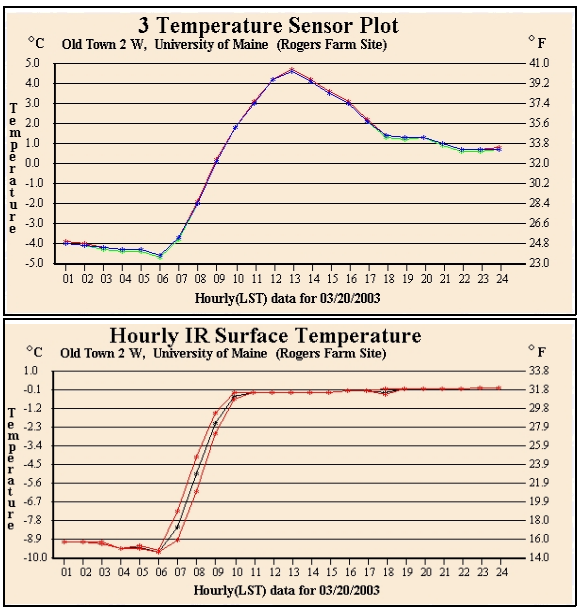

Figure 4. Ambient and IR Temperatures for Old Town, ME

7. WIND SPEED DATA

The last meteorological element to be discussed is that of wind speed. Just as with the previous two elements, wind speed is also involved in the transfer of heat from the ground to the air above during the day and the modification of heat loss from the ground at night. Calm wind conditions allow the ambient temperatures to rise higher during a clear day and drop further during a clear night. This is particularly true if the site is in a valley, but it is much less true of a site that is located on the side or top of a hill. Usually the maximum temperatures at valley and hill top exposures will be similar, however during clear nights the minimum temperatures can be as much as 5° to 10° C colder at the valley site.

Once again the importance of site documentation should be emphasized. This documentation must include photographs of the local site, its geographic relief, and vegetative cover. These elements are critical in the correct manual or automated QC of ambient temperature and wind speed. The photographs of the USCRN sites become a part of the extensive METADATA files maintained with the USCRN data archives. As was mentioned previously the wind speed data at the USCRN sites is measured at the same height as the intakes of the aspirated ambient temperature shields. This is true even at those sites where all sensors are mounted higher to keep them about 0.6m above the level of the 100 year maximum snow depth.

The wind speed data are also used in making comparisons between the recorded precipitation of the shielded USCRN gages and the precipitation values recorded at nearby climate stations that have no wind shields. Even though it is an unintended benefit, manual QC currently uses a frozen wind speed sensor as a supplementary confirmation of a freezing rain event.

8. BATTERY VOLTAGE

As in the case of the fan speed data, USCRN QC does not adjust or change any of the reported battery voltage values. There are, however, range limits that when exceeded cause error messages/ flags to be sent to the QC and database. They are extremely valuable in defining the cause of a fan problem or loss of transmission from the data logger. The batteries at most USCRN sites are charged by Alternating Current (AC) from the local power grid. The AC power keeps several large batteries charged through the means of a “trickle charger” and it is from these 12 volt batteries that the data logger, fans, heat tape, and instruments are powered. The large batteries serve to absorb most of the power surges, as well as providing power to the station equipment up to four days in the event of a loss of power from the grid. Several of the USCRN sites are solar powered and thus are charged by a series of solar panels. Obviously the batteries at these sites are charged only during the daylight hours and thus have a diurnal cycle to the level of battery voltage. The resulting variation in the voltage also causes a diurnal pattern in the fan speeds, but are still within nominal levels. Therefore, if a fan speed decreases while the battery voltage is stable or rising then there is a problem in the fan or its connections. An interesting side light to the issue of diurnal cycles of the fan speeds is that the fans are sensitive to the density of the air. The warmer the temperature the lower the density of the air and the response of the fans to the lower density air is to run at a faster

speed. Also then a fan will run faster at a higher altitude at a given temperature. The upper flag limit for fan speeds had to be raised to accommodate the fans at the Boulder, CO, site that is at an elevation of 3034 m (9950 ft).

Battery voltages are monitored for three separate conditions in the instrument system. The first is the voltage to the fans and GOES transmitter, the second is the voltage to the fans and GOES transmitter under full load, and the third is the voltage to the data logger. The lower level flag limit of the first location is 12 volts, the second 11 volts, and the third is 10 volts. The system has been designed to shut down everything but the data logger when the voltage drops below 10 volts so that it can continue to store the last five months of data for later down load (if needed) to a palm pilot or laptop computer. This redundant storage and recovery process has enabled a greater than 99 % complete data set for the USCRN program over the last two years.

9. CONCLUSION

The quality control of the USCRN data will continue to improve over the next months and years as the station network plans to expand to more than 100 stations. Current global and annual flag limits will be refined to individual station month limits. Complex QC algorithms will also be added to look for any subtle drifts in the archived values. Knowledge learned from manual QC of the data will be integrated into the algorithms of the automatic QC and thus standardize the review and flagging of the more routine sensor excursions while at the same time giving more time to manual efforts in analyzing problems of a more complex nature. Interaction with individuals or institutions with local climatological knowledge such as State Climatologists and Regional Climate Centers are welcomed and hopefully will increase as more stations are installed.

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