United States Climate Reference Network Part of NOAA's Environmental Real-Time Observations Network

FY2005 Annual Report

NOAA-NESDIS (USCRN)

NOAA-NWS (NERON)

October 2005

USCRN Web Site: http://www.ncdc.noaa.gov/oa/climate/uscrn/index.html

NERON Web Site: http://www.nosa.noaa.gov/descriptions/nws/neron.html

U.S. Department of Commerce

National Oceanic and Atmospheric Administration (NOAA)

National Environmental Satellite, Data, and Information Service (NESDIS)

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1. Introduction

This is the third annual report for NOAA's United States Climate Reference Network (USCRN). The primary focus of this report is on the FY2005 USCRN development and implementation activities. Initial projections of activities planned for FY2006 are included. FY2000-FY2003 USCRN activities were reported in the USCRN FY2003 Annual Report, and FY2004 activities in the USCRN FY2004 Annual Report.

This report include reviews of the USCRN, Performance Measures, stations installed, research progress, instrument testing, partnership activities at several levels, data quality, data availability, and as well as progress in coherence, compatibility, and complementarity of the USCRN with the forthcoming modernization of the US Historical Climatology Network (USHCN-m). This report also includes a tentative projection of the USCRN deployment phase completion date (FY2008) and maps and tables showing the present view fo the final geographical configuration of the USCRN.

2. Program Base

The required program capability and requirement drivers for the United States Climate Reference Network (USCRN) are the following:

2.1 Program Capability

The NOAA Strategy of "Monitor and Observe":
"We will invest in high-quality, long-term climate observations and will encourage other national and international investments to provide a comprehensive observing system in support of climate assessments and forecasts." (NOAA Strategic Plan)

2.2 Program Purpose

The USCRN program will provide the United States with a climate monitoring and climate change network that meets national commitments to monitor and document climate change. The USCRN Program will deploy no fewer than 100 operational sites in the continental United States through FY 08 to achieve this goal. The program purposes are to:

a.) Ensure that future changes and variations in primary measurements at specific locations can be monitored without the need for uncertain adjustments and corrections to the data. Primary measurements at each site will include air temperature and precipitation supplemented with other measurements such as wind speed, solar radiation, and infrared radiation. Envisioned improvements during FY2006-2008 include addition of sensors for the measurement of Relative Humidity, Soil Moisture, and Soil Temperature.

b.) Ensure that the network will provide adequate spatial coverage to monitor the annual and decadal-to-centennial temperature and precipitation trends at the National Scale for the United States.

c.) Maintaining the fundamental requirement of establishing a network that 50 years from now will answer the question: How has the climate of the United States changed over the past 50 years?

d.) In accomplishing this goal, ensuring that the program adheres to the Ten Climate Monitoring Principles[1] as defined by National Research Council of the National Academy of Sciences (see Appendix A).

The program requirement drivers and program objective and characteristics are given below.

2.3 Program Requirement Drivers

A. <u>Legislative:</u>
Federal Data Quality Legislation (Act) (Public Law 106-554 Section 515) - Section 515 is known as the Data Quality Act … government must assure the quality of the information disseminated.
15 USC 313 "establish and record the climate conditions of the United States"
Global Change Research Act of 1990 -- "requires an early and continuing commitment to the establishment, maintenance, global measurements, establishing worldwide observations… and related data and information systems"
44 USC 31 PL 81-754 Federal Records Act of 1950 provides for Agency Records Center and in 1951 the National Weather Records Center established an Agency for U.S. weather and climate records with responsibilities of archiving and servicing.
33 USC "… authorize activities of processing and publishing data…"
15USC CH29 PL 95-357 National Climate Program Act authorizing "…. Global data collection monitoring and analysis…"; "…management and active dissemination of climatological data…"; and "… increase international cooperation … monitoring, analysis and data dissemination"

B. <u>Executive/International/Programmatic</u>

Earth Observation Summit (and Group on Earth Observation (GEO) Working Group) – Summit Declaration reaffirmed need for timely, quality, long-term global information as a basis for sound decision-making and called for filling data gaps. Summit Declaration also affirmed need for "producing calibrated data sets in useful formats from multiple sensors and venues".
Climate Change Science Program Strategic Plan – has a number of goals articulated including: "complete required atmosphere and ocean observation elements needed for a physical climate observing system" – this includes the "US Climate Reference Network" as an underpinning for providing the highest quality benchmark data for enabling the determination of transfer functions with other U.S. meteorological networks such as ASOS, SURFRAD, and COOP; "Data archives must include easily accessible information about the data holdings, including quality assessments, supporting ancillary data, and guidance and aid for locating and obtaining data" and "Preservation of all data needed for long-term global change research is required. For each and every global change data parameter, there should be at least one explicitly designated archive."

Global Change Observing Systems Second Adequacy Report – Concerning data accessibility and quality, "There are many observations of the climate system already being taken today. The report notes many times where there are issues with respect to the limited accessibility to much of the data and problems with its quality. Addressing these issues would have an immediate and positive impact on the ability of the current global observing system for climate to meet the needs of the Parties." More pointedly, the Report states "Notwithstanding the use being made of current information and improvements made in the past few years, this report confirms the IPCC view that current observations are not adequate to meet the full needs of the Parties and are an increasing barrier to the full provision on advice. Without urgent action … the Parties will lack the information necessary to plan for and manage their response to climate change."

World Climate Programme Data and Monitoring (WCDMP) Guidelines on Climate Observation Networks and Systems (WCDMP No. 52) and Guidelines on Climate Metadata and Homogenization (WCDMP No. 53).

These WMO documents were written to identify the "best practices" for climatological observations, data collection, metadata, and archival activities. The intent of the documents is to bring all WMO members up to similar standards using the Ten Primary Climate Principles (see Appendix A) as a base. Using these standards for USCRN implementation, the USCRN stations and instrumentation are qualified as "Principal Climate Observations Stations" and "Reference Climate Stations."

Annual Guidance Memorandum – "Taking the pulse of the planet – contributing to an Integrated Global Observing System" and that "we should develop a comprehensive, NOAA-wide data collection, quality control, storage, and retrieval program."

Several bi-laterals, particularly, U.S/Canada Weather/Climate, and the Global Change Observing Systems (GCOS) initiative to stimulate CRN-like initiatives in Latin America, and eventually to other regions.
U.S. Climate Change Research Initiative – work to improve global observing systems, including involving those of and/or being built by developing countries; work to improve access to global observations.
The Administration position is outlined in a speech by President George W. Bush in June 2001 enjoining the climate community to provide decision-makers with the most precise, least controversial climate data and trend analyses than any previously possible in order that public policy decisions of great gravity could be made with the highest confidence.
The philosophical-technological base of the USCRN is derived from the Climate Monitoring Principles as initially formulated with and reviewed by the government and academic climate communities in 1999[2.] (See Appendix A).

2.4. Program Objectives and Characteristics

The USCRN program objectives are to develop, acquire, field and operate the premier environmental climate-monitoring network of the United States. The USCRN provides stable surface temperature and precipitation observations that are accurately representative of environmental conditions. Site location is particularly important as environmental conditions must not be affected by encroachment of urban expansion or other conditions that create a changing environment.

As the premier reference network providing data for the climate science community, USCRN site locations must remain stable for a period of 50 to 100 years. Where possible, USCRN stations are being co-located with or near existing meteorological observation sites such as those of the Historical Climate Network (HCN), the National Weather Service's Cooperative Observer (COOP) and Modernized COOP networks, the Canadian Reference Climate Network (RCS), the NWS Automated Surface Observing System (ASOS), the Bureau of Land Management/Forest Service Remote Automated Weather Stations (RAWS), the NOAA Surface Radiation Network (SURFRAD), the University of New Hampshire's AIRMAP stations, and various State mesonet stations. As the USCRN is intended to serve as a model environmental monitoring network for the United States and the international community, the program will develop data transfer functions relating observations between those networks and the USCRN to thereby leverage primary and specialized climate observations over broader coverage areas.

USCRN field system technology is designed to be highly reliable, precise, robust and maintainable so that it collects, formats, processes and communicates measurements of environmental parameters to NOAA's National Climatic Data Center's (NCDC) central data management and processing facility in Asheville, N.C. Network data ingest for FY2005 averaged 99.9% (see Appendix C, Tables A and B). The equipment at USCRN field stations is designed to operate, without human intervention, under a wide variety of environmental conditions. The NCDC provides data ingest, quality control monitoring, data processing, archiving, and user access capabilities to both the climate research community and the general public.

After four years of development and implementation, the USCRN stations thus far deployed were verified as having sufficient spatial distribution, reliability and stability, and science information value that NOAA formally commissioned the network in January 2004. The desired outcome, capabilities required, and program-level performance measures of USCRN are discussed below.

2.4.1 Desired Outcome

The USCRN is a sustained, cost-effective science-driven national and regional climate data and benchmark system complementary to older and less rigorous or less precise NOAA in-situ (surface) networks. USCRN provides reliable information related to the state and changing state of the climate system and enables more reliable and higher-confidence climate-related predictions and projections to be made by both national and regional decision-makers.

2.4.2 Capabilities Required

The required capabilities of the USCRN are the following:

a. Provides land-based reference stations and standard land surface observing stations for tiered NOAA ground observing systems such as NOAA's COOP and ASOS networks.
b. Coverage must be of sufficient temporal and spatial resolution to monitor local-to-national spatial scales for physical phenomena and to determine with the highest confidence trends of significant socio-economic and scientific importance.
c. Measurements of key variables adhering to NRC and GCOS/WCDMP Climate Monitoring Principles. The two primary variables for USCRN are very high-quality, redundant measurements of temperature and precipitation, with secondary variables of solar radiation, wind velocity, and infrared radiation being used as primary variable checks.
d. Data, assimilation, archival, and product generation subsystems for the observations.
e. Observing system management and information delivery infrastructure.

2.5 Program-Level Performance Measures

The programmatic level Performance Measures for the USCRN are built upon the simplest, cleanest, most basic purpose of the network:

To reduce the uncertainty in the quality of the data and minimize the error in the measurements in order to produce the most accurate in-situ temperature and precipitation records possible, and to do it with the fewest possible stations located in areas of minimal human disturbance and with the least likelihood of human development over the coming 50-100 years.

Therefore, the highest level, single goal of USCRN is to reduce Climate Uncertainty at the national level to a statistically insignificant level.

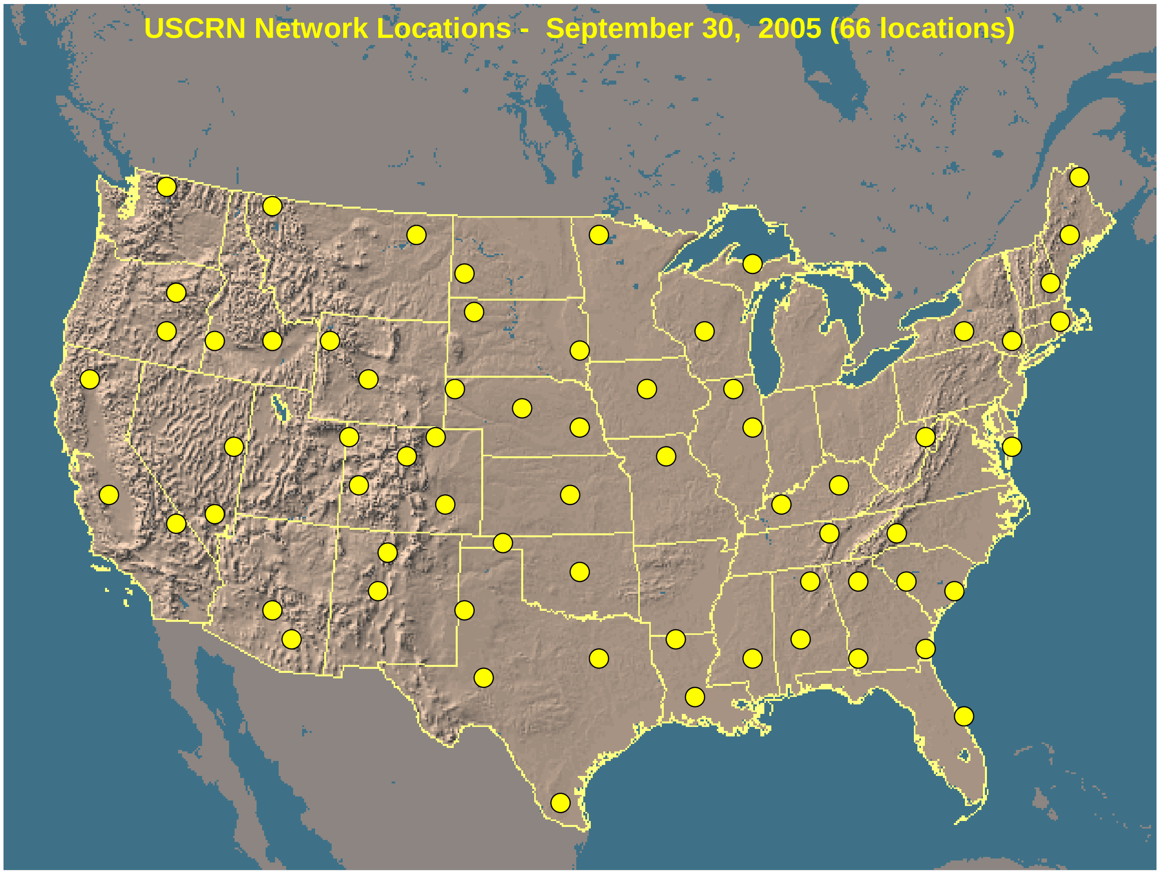
End goals for development of this primary USCRN Performance Measure are for Temperature Climate Uncertainty at the national level to be reduced by at least 98%, and for Precipitation Climate Uncertainty to be reduced by at least 95%.

For reduction of Climate Uncertainty for the individual nine U.S. Standard Climate Regions of the CONUS to similar values as at the national level, the USCRN would require that the spatial density of the USCRN grid be increased to >300 stations.

By the end of FY2005 station deployments in the Continental U.S. (CONUS, which excludes Alaska, Hawaii, and the various Territories) reduced National-level Climate Uncertainty for temperature by over 96%; the precipitation Climate Uncertainty was reduced by over 91%. This lag of the precipitation PM behind the temperature PM is normal due to the greater temporal and spatial resolution needed to estimate with confidence either the normal and abnormal behavior of precipitation.

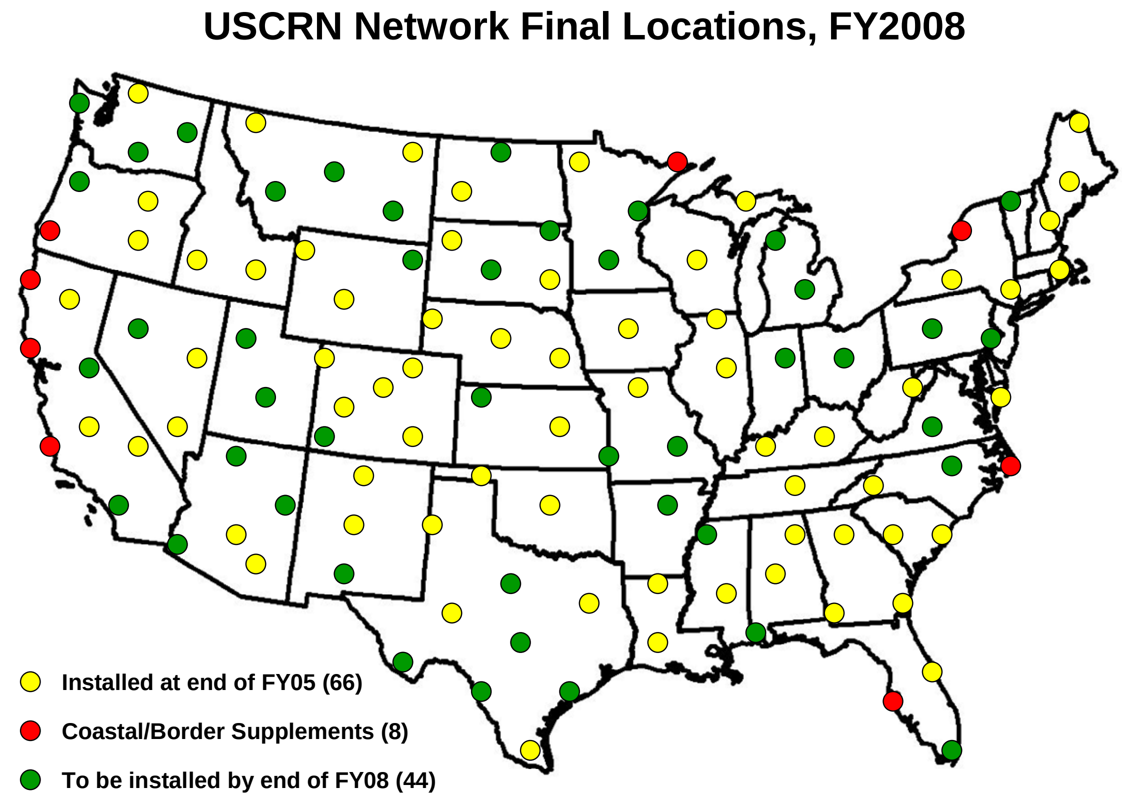
FY2005 reductions of Climate Uncertainty were hampered by fewer than planned station deployments due to being provided with an insufficient budget as to reach the FY2005 goals and Performance Measures. As of September 30, 2005, the USCRN network now consists of 72 commissioned field stations at 66 locations within the CONUS (see Fig. 1 below). The apparent inconsistency of the greater number of stations (72) as compared to the deploy locations (66) is an artifact of the early-stage 2002-2002 station pair deployments. At that time the USCRN was envisioned to consist of 500 twinned stations at 250 locations. The current program consist of CRN commissioned field stations located at 110 field locations.

Figure 1. Map of USCRN CONUS Deployed Locations Through FY2005



The Climate Reference Network (CRN) established ?? stations in 2005 in the contiguous 48 states. There were also new stations installed in Alaska and Hawaii that are part of the Global Climate Observing System. There was also a Canadian version of a Climate Reference Network station installed side-by-side with the Canada at EROS. The site in Mississippi lost electricity for several days after Hurricane Katrina, but solar panels were installed before the batteries lost power so no data were lost. The amount of rainfall in the event was ??. Although the CRN is has the main purpose to track climate change and variability at the annual, national level, the quality and robustness of the data are valuable for assessing extreme events such as hurricane precipitation. Progress in reducing the climate uncertainty to the required national level comes in smaller increments and is approached asymptotically as the CRN nears completion in 2008. CRN will be complete when more than 40 additional CRN stations are deployed across the continental U.S. at specific geographic locations to meet the minimum acceptable program goals of national decision-maker needs for high-confidence science support (Figure 2).

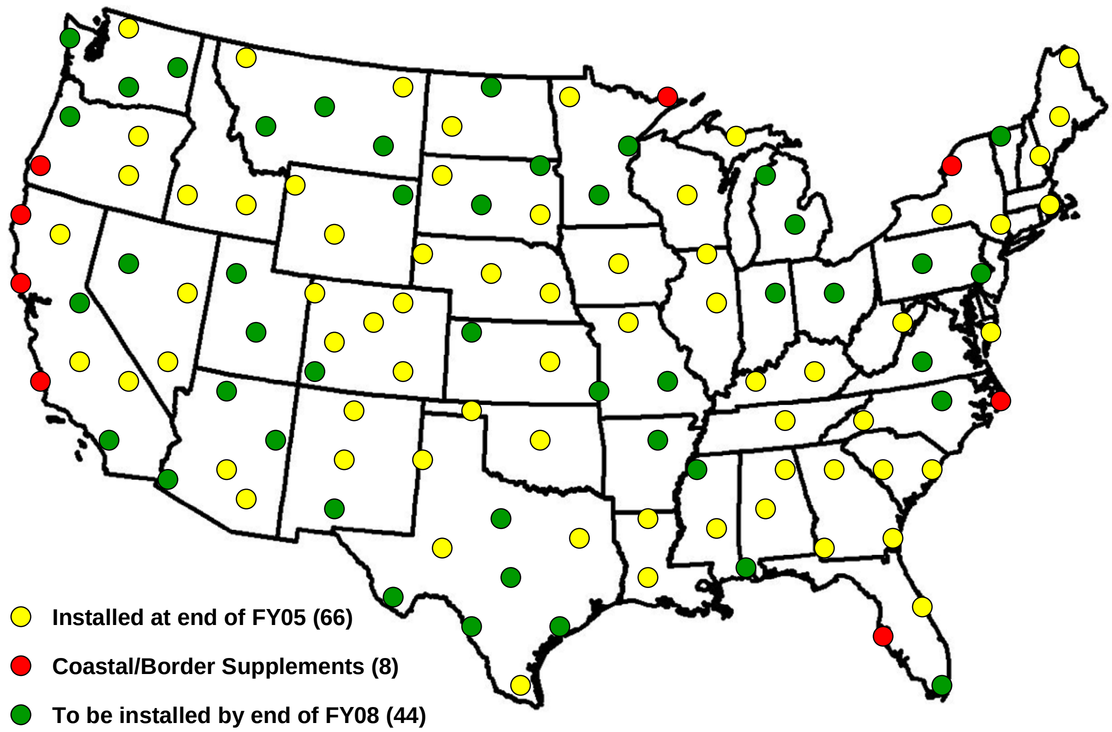
Figure 2.



Funding limitations during FY2005 resulted in only 10 CRN stations being deployed in the CONUS by September 30, 2005. This FY05 funding shortfall also delays the completion of the USCRN network into FY2008.
(For a fuller discussion of the apparent discrepancy between the total number of USCRN stations versus the number of commissioned field stations in the CONUS please see Sec. 4.7)

Reductions in Climate Uncertainty were most pronounced and even dramatic in the first part of the program, FY2000-2004. Progress in reducing the climate uncertainty to the required national level comes in smaller increments and is approached asymptotically as the USCRN moves into the end phase of the station deployment campaign during FY2005-2008. More than 40 additional USCRN stations deployed in a specific geographic pattern are required in the FY2006-2008 period to meet the minimum acceptable program goals of national decision-maker needs for high-confidence science support. An additional eight (8) coastal and border locations are recommended for station deployments not yet funded. A map of the finished USCRN net and its configuration is in Figure 2 below. Names of the installed, planned, and recommended station locations are provided in Table 1. Common color codes are used to represent the status of location dots on Figure 2 with the location names listed in Appendix B.

Figure 2.
USCRN Network Final Locations, FY2008



Additional or unplanned funding (e.g., earmarks) that are pointed towards putting in additional USCRN stations that do not fit on or near USCRN grid points do not necessarily decrease National Climate Uncertainty levels – and they may initially diminish the Regional or Local Climate Uncertainty levels. Any additional or accelerated deployments should be made within the boundaries and grid points developed for the USCRN program. Off-grid additions such as the two FY2005 Alabama stations deployed in April and May 2005 can be useful if they are representative of a climate region that is not otherwise monitored. In the case of those two late FY2005 stations, their deployment provided no decrease of the National Climate Uncertainty figures.

An additional question that this supplementary station funding accentuates is how does the USCRN provide for the annual maintenance and re-calibration of these additional stations except by cutting corners throughout the network. Our Operations & Maintenance budget is very tightly estimated. Earmarked station additions erode into that budget line unless the O&M outyear line is proportionally increased. Thus far, there has been no additional O&M funding for earmarked stations. Conceivably, further uncoordinated station additions may erode the overall network data quality over time as maintenance and re-calibration, etc., may have to be spread too thin to maintain required specifications at all stations. These issues need to be carefully documented to see what the long-term impact might be of what are envisioned as front-end improvements of the net.

These unplanned stations may gradually rise. As new stations (e.g., the Alabama stations) are added, we include them in the total station numbers, but they do not necessarily contribute to or accelerate our PM goals, nor do they replace the need to cover all the required grid points. They also impact our outyear maintenance and operations budget that is critical for long-term network science confidence and credibility. Based on the past four years of Annual Maintenance Visits (AMV), the average annual cost for each station's maintenance/re-calibration and equipment upgrades is about $3.5K/yea, so there are only slight impacts thus far. It is noted that there are geographical differences in the cost of AMV's depending upon station location.

It would take another five years (FY2009-2013) and a significant increase in the number of USCRN stations to attain similar climate variance confidence levels for local, State, and regional decision-makers as those being developed for the National Decision-Makers by the core 110 commissioned field stations of the USCRN. That number of 110 stations does not include engineering and test sites, purchased Stations, or those stations provided by additional Congressional earmarks – and which are located in areas off of the smallest possible deployment grid developed for USCRN.

Tables 1a and 1b below demonstrate the relationship between the number of USCRN stations deployed and the reduction of the National Performance Measure of Reduction of Climate Uncertainty for both Temperature and Precipitation::

Table 1a. US Climate Reference Network Performance Measures,

FY2002-2008, TEMPERATURE

U.S. Climate Reference Network	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006	FY 2007	FY 2008

(USCRN)							
PM: Reduce climate uncertainty concerning variability of temperature trends to required levels for monitoring climate variability and change.							
National Goal – % of Climate Uncertainty (precise %)	26	<20	<5	<4 *(2.5)*	<3 *(1.5)*	<3 *(1.7)*	<2 *(1.8)*
Regional Goal – % of Climate Uncertainty (precise %)	94	<65	<15	<10 *(5.6)*	<10 *(6.3)*	<8 *(7.2)*	<7 *(4.7)*
# of Sites to reach National Goals[1]	23	40	67	72	88	104	110*

****Commissioned field stations*.**

Table 1b. US Climate Reference Network Performance Measures,

FY2002-2008, PRECIPITATION

U.S. Climate Reference Network (USCRN)	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006	FY 2007	FY 2008
PM: Reduce climate uncertainty concerning variability of precipitation trends to required levels for monitoring climate variability and change.							
National Goal -% of Climate Uncertainty (precise %)	26	<20	<15	< 8 *(6.9)*	<8 *(5.2)*	<7 *(5.0)*	<5 (4.4)
Regional Goal -% of Climate Uncertainty (precise %)	94	<25	<24	<23 *(20.1)*	<22 *(18.3)*	<21 *(18.3)*	<20 *(18.0)*
# of Sites to reach National Goals[1]	23	40	65	72	88	104	110*

**Commissioned field stations*.

[1] *For the Lower 48 States of the continental United States, a total of 110 commissioned field stations are needed to meet the primary, composite (T & P) National Performance Goal of Reduction of Climate Uncertainty to required levels. Test, engineering, and other sites are not included in the commissioned field station total number of 110. Earmark and other unplanned station additions may or may not count against the 110 station total depending upon their geographic placement. Thus the present two Alabama station are*

both commissioned field sites, but they do not result in PM augmentation because of their off-grid locations.
Numbers in parentheses are the exact run percentages for each year as determined from the Monte Carlo simulation guidance software.

3. FY 2001-2004 Achievements:

The USCRN achievements, Milestones, and Performance Measures were presented in detail in the USCRN FY2003 and FY2004 Annual Reports, previously submitted.

4.0 FY 2005 Achievements

In FY2005 the USCRN Program was organized and prepared for a large deployment year as well as continued testing and development of existing, new (next-generation), and supplemental sensors, bringing to maturity both the temperature and precipitation algorithms, and converting, formatting, and standardizing a large backlog of station and instrument metadata to be posted on our Internet site. Additionally, USCRN was encouraged to assist the startup processes involved in the NOAA NERON and USHCN-Modernization programs.

The USCRN program is one of NOAA's best examples of research-to-operations. Overall the USCRN program has become a model for NOAA in terms of in-situ observing systems. In FY2005 two additional observing systems have adopted using the same instrumentation, sampling period, and algorithms for the measurement of precipitation. These two networks are the Canadian Reference Climate Network and the modernization of the COOP program. In addition, the NOAA NERON and HCN-Modernization programs are utilizing the same infrastructure as the USCRN. This cross-matrix within NOAA sets the example of having two in-situ observing systems that are utilizing the same line offices for acquisition, engineering, calibration, site surveys and installation. This level of cooperation within NOAA optimizes and capitalizes on fiscal and human resources across multiple line offices for two in-situ networks within NOAA.

In summary, CRN is undertaking the normalization and infrastructure activities that mark a mature and healthy network that has both a well-defined purpose (mission), but one which still has the youth and energy to evolve, experiment, and strengthen data meaning and applicability.

The program is approaching an operational network status with 65% of the required minimum 110 field station locations to be deployed. The station deployments are underlain by a robust infrastructure that includes full documentation of the metadata, timely response to unscheduled repairs, summary and monitoring of all maintenance reports, action item notification chain and check, and quality control/quality assurance of the data. The customers for the data include BLM, EPA, USDA, NOAA, USGS, NPS, NSF, NOAA's Regional Climate Centers, State Climatologists, and many others. The continued emphasis upon a strong science component for the USCRN has established and improved the precision and accuracy of the sensors. This has resulted in other international and national networks utilizing USCRN instrumentation and data processing algorithms.

4.1a FY2005 Performance Measures: Climate Uncertainty

During FY2005, the USCRN network increased in number to 72 commissioned field stations and ten other off-grid or engineering/test sites, for a total of 82 stations (not all funded by USCRN, see Sec. 4.7).

The full schedule of deployments planned for FY2005 did not materialize as the USCRN budget was effectively zeroed late in FY05Q1. Although funding was found to preserve operations and maintenance, most remaining planned FY05 deploys were cancelled and no new research or engineering tests and programs were undertaken for the last three Quarters of the year. This funding shortfall had two principal impacts on the USCRN primary Performance Measures during FY2005

a. These deployments reduced the National Climate Uncertainty below the levels originally planned by the end of the year. By September 30, 2005, our PM for temperature is 96.9%. Likewise the precipitation PM stands at 91.9%

b. The Regional Climate Uncertainty PM for Temperature was reduced to >10%, and that for Precipitation was reduced to 23%.

4.1b FY2005 Performance Measures: Data Ingest

A secondary Performance Measure, Data Ingest, gives a measure of how many of all possible field station measurements were successfully transmitted and then received in the National Archive (NOAA's National Climatic Data Center). The higher the percentage, the more effective are the station maintenance program and the communications systems, and the more confident is the scientific community's interpretation of the dataset. This Performance Measure is a quantitative measure of how robust the network is. In shorthand, the higher the Data Ingest percentage, the fewer problems there are with the individual stations as well as with the network as a whole. The planned high performance target at the program outset was envisioned to be a Data Ingest percentage into the NCDC Archive of 98% of all possible station observations in a timely fashion (e.g., within 30 days). The lower limit of acceptability of dataset completeness in the climate science community is generally held to be 95%. As a result the CRN Performance Measure of 98% was felt to be so high, based on data ingest percentages from previous networks, that it was initially felt possible that the CRN was planning for failure rather than for success.

The USCRN network integrity was severely tested in the Southern CONUS during the passage of Hurricane Katrina across three CRN commissioned field stations in Mississippi (Newton, MS) and Alabama (Selma and Gadsden). Although the primary electrical grids at two of the stations went down during the storm – no sensors or other station components were lost and backup station battery packs worked as planned. As a result of the station redundancies and overall robustness, 100% of all possible storm observations were ingested at NCDC from all three stations prior to, during, and after the passage of Katrina. The lengthy downtime of the Mississippi electrical grid did necessitate an emergency visit to the station as its on-board batteries were running low. The team visited the site when it was possible to get to it, nearly a week after the storm's passage, and successfully converted it from an AC-powered to a solar-powered station with about 7 hours of on-station battery time remaining. Although prepared for other contingencies, no further repairs to the station were required in what was otherwise a landscape of devastation.

Although the precise track and onshore intensity of Hurricane Rita, following shortly after Katrina, was different the same Mississippi-Alabama station set plus two Louisiana stations (Lafayette and Monroe/Ouachita) and one Texas station (Palestine) in or near the path of Rita also survived intact and with no missed observations.

Equipment deficiencies and station hardening techniques are being studied for improvements. Certainly one improvement that these hurricanes demonstrate is that two-way communications with the station would provide remote capabilities which would allow station power budget and sensor priorities to be more tightly controlled for maximum survivability and duration of service in the aftermath of such storms. This would allow a lengthier battery operation of the primary Temperature and Precipitation sensors. This should be a priority network improvement that may require a supplement to capture critical data before, during, and after various natural disasters.

Since the USCRN program began in FY2001 this Data Ingest Performance Measure has been gradually increasing to a level at least equal to what the climate science community has specified is an acceptable base level for support of exacting climate science studies (a minimum of 95% completeness for a data set as an acceptable level, with 98% completeness as a preferred level of data completeness). This 98% base level was first reached in the 1st Quarter of

FY2002. The Data Ingest has now sustained itself above the 99% level since the 1st Quarter of FY2003. During the last two Quarters of FY2005, the data ingest was 100.0%. There is no expectation that 100.0% will be sustainable over the longer term. Tracking of this Performance Measure is portrayed in Table 2 below:

Table 2.
USCRN Observations: Network-Wide Data Ingest (%)*,
FY2001-2005

FY	Q1	Q2	Q3	Q4	Annual
2001	**86.8**	**96.5**	**70.5**	**97.4**	**87.8**
2002	**95.4**	**96.1**	**98.4**	**96.7**	**97.0**
2003	**98.5**	**99.4**	**99.8**	**99.5**	**99.4**
2004	**99.9**	**100.0**	**99.8**	**100.0**	**99.9**
2005	**99.9**	**99.9**	**100.0**	**100.0****	**99.9****
Average	**96.1**	**98.3**	**93.7**	**98.8**	**96.8**

**Percentage of all possible measurements received in the National Archive (National Climatic Data Center) and made available via the Internet.*
NOTE: Previous yeasr data ingest percentages have been slightly improve by small amounts due to early 2005 complete re-reading of PDA's after those earlier reporting periods were closed.
***Latest data available for FY054Q4 is 30 August 2005.*

The data and progression of data ingest figures at a high plateau level of >99% for the past eleven Quarters indicates that USCRN technologies, redundancies, and communications layering have produced a highly reliable, multi-layered, and robust climate monitoring network. USCRN meets the most stringent climate science criteria (98% data ingest rate) developed by NAS-NRC and the WMO.

The very low FY01Q3 70.5% Data Ingest is due to major upgrading of the two field prototypes (the Asheville NC stations) during that Quarter. These were the only two stations in the network at that time. This downtime resulted in data gaps while the upgrades were being made. Field station deployments did not take place in large numbers until FY2002, thus an argument can be poised that FY2001 was a prototyping, experimental year and, perhaps, should be excluded from network-wide statistical summaries and studies.

A solid improvement from the FY2002 Q1 of 95+% data ingest level has now plateaued with sustained very high data ingests (99+%) in October 2002 through FY2005. During this period the network has increased from two prototypes to 72 commissioned field stations. CRN technology is behaving at a mature level; maintenance programs are both proactive and reactive -- and they are effective. Layered communications have made the difference between good performance and outstanding performance.

USCRN FY01-04 and some early FY2005 data has been recovered from station dataloggers using PDA's downloaded to NCDC archives (see Appendix C Tables). The network Data Ingest PM for the cumulative period FY01Q1 through FY05Q4 is 99.6%. In the latest two network quarters (FY05Q3 and Q4), the preliminary Data Ingest PM is 100.0%.

4.2 FY2005 Installations and Surveys

FY2005 installations and surveys included the following activities:

Site Surveys – 24

Sites Approved – 12

Site Licenses Signed – 15

Stations Installed – 10*

The new CRN field stations installed in FY200 by month are:

October 2004	Ithaca, NY	(USCRN funding)
	Necedah, WI	(USCRN funding)
November 2004	Chatham, MI	(USCRN funding)
	Millbrook, NY	(USCRN funding)
December 2004	Brunswick, GA	(USCRN funding)
	Crossville, TN	(USCRN funding)
January 2005	No deploys	
February 2005	No deploys	
March 2005	No deploys	
April 2005	Gadsden, Alabama	(external funding)
May 2005	Selma, Alabama	(external funding)
	Titusville (NASA-KSC), FL	(USCRN funding allocated for November 2004 deployment. The deploy was delayed by NASA technical & construction problems the near CRN site at the south end of the Space Shuttle runway.

June 2005	Chillicothee, MO	(USCRN funding – Deployment of opportunity coupled with CRN engineering preparation trip for nearby deploy of Canadian station)
July 2005	No deploys	
August 2005	Sitka, AK	(GCOS funding)
	St. Paul, AK	(GCOS funding)
September 2005	Mauna Loa, HI	(GCOS funding)
	Waiakea, HI	(GCOS funding)

The locations of these stations are portrayed on the map (Figure 1).

4.3 Breadth of USCRN Station Partnership Net

The organizational classification of USCRN operational field stations by Host Agency identity gives an indicator of the breadth of the USCRN partnership involved in the building of this network. The Site Hosts are critical for proper maintenance, some emergency maintenance, and landscape care at each CRN commissioned field site. In the instance of CRN, each Site Host receives training, maintenance technique familiarization training, and instructions manuals and compact discs of information on how to clean and/or replace modular equipment for optimum operations, check for common singularities, irregularities, and failures of equipment and sensors. New spare parts are sent if failures occur via express-service mailings, and Site Hosts replace theses as necessary. For major failures such as lightning strikes, damaging electrical surges, severe storms, vandalism or animal damage, an emergency maintenance team from the NOAA-ATDD partner will be sent to the station to bring it on-line and to certify its correct operation. Table 4 below shows the type of Partner who comprise the CRN commissioned field station first response team for USCRN network problems. These Site Hosts are an essential part of the overall USCRN team.

Table 3

CRN Hosts*- September 2005

- Arboretum/Audubon/Foundation - 9
- University – 32
- Native American Indian Reservation – 2
- State Parks and Forests – 3
- NOAA facilities – 4
- National Wildlife Refuges – 7
- National Park Service – 14
- Other Fed (Ag, NASA, USGS, DOE, BLM, Can) - 9
- Test sites - 2

*all stations (test, commissioned and non-comm, Alaska, Hawaii, Canada.)

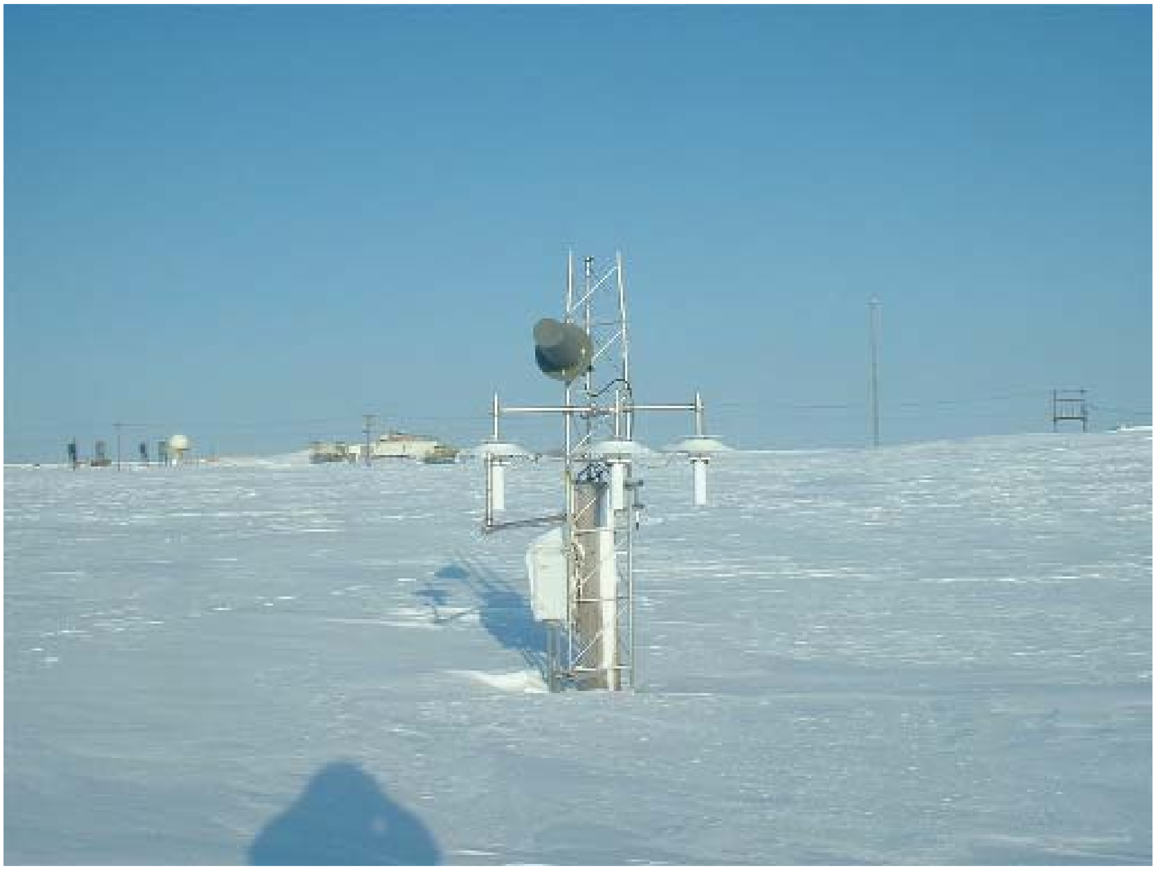
4.4 FY 2005 Sensor Testing and Science Studies

Work continued in FY2005 on developing relationships between USCRN and other national and international climate networks. CRN presentations at national and international conferences continue to result in inquiries from abroad in linking or exchanging technology, developing common observing, archiving, operating, and siting standards worldwide.

Canada is the only nation, thus far, with a formal relationship with USCRN. Late FY2005 talks indicate that it is possible that CRN technology may be extended to other countries/regions during FY2006. Queries are developing through the NOAA International Polar Year Office for the deployment of a CRN station into Northern Siberia (the Tiksi area at the mouth of the Lena River) in FY2007 if annual maintenance and calibration arrangements can be successfully developed.

Interworking and developing relationships with the NWS personnel in the NOAA COOP and HCN-M programs continue to evolve. There has been agreement between these programs of using a downscaled version of the USCRN equipment for some applications. This agreement is a cooperative effort between NCDC, ATDD, and NWS. Our OAR partner, ATDD, has been an exemplary engineering team and have developed numerous new components for the USCRN, modified existing components to improve the measurements, and have engineered the new system that has been adopted for the NERON program and have proven the operation of USCRN stations in harsh environments.

Typical of these efforts has been the development of a darkened fiberglass cover for the CRN yagi antenna to GOES. This cover prevents ice and snow buildup from occurring and provides a sufficiently smooth surface that birds find it difficult to roost thereupon. The antenna cover (pictured below at the Barrow, Alaska station) is being retrofitted to those stations particularly at risk from iced/snow problems.



USCRN Station in Barrow Alaska

The USCRN and NERON programs have also agreed to co-locate selected NERON sites at USCRN stations. Data from co-located instruments supports and speeds temperature and precipitation transfer function developments between networks. This leverages climate- quality observations to higher-density grids from which USCRN is resource-constrained. This co-location and transfer function activity is planned to continue indefinitely. Co-locations also provide new elements of data continuity and station survivability. Increased emphasis upon these factors has come into sharp focus since the passage of Hurricane Katrina across Louisiana, Mississippi and Alabama in late August 2005. Missing data ingests from various networks in those three States during this hurricane indicate that non-CRN station/sensor destruction and/or data outages have occurred in some operational networks. The missing data is critical for extreme hurricane analysis. USCRN stations in the area survived and have provided 100% of all observations to the data archive (NCDC) before, during, and after the event.

A USCRN temperature and relative humidity (RH) testbed is examining accuracy and reliability of Relative Humidity (RH) sensors which may be integrated into the entire CRN network. This integration activity will probably be scheduled for FY2007 and FY2008.

Work continued in FY2005 on developing relationships between USCRN and other national and international climate networks.   Recent CRN presentations at national and international conferences, strong interest in linking or exchanging technology, observing standards, and data has been received from nations in Europe, Latin America, Asia, and Australia. Canada is the only nation, thus far, with a formal relationship with USCRN and is in the process of co-locating a Canadian Reference Climate Station with a USCRN station in the United States.

Results from two years of rigorous measurements at the two testbeds have encouraged the Canadian Reference Climate Network to use the USCRN precipitation gauge and to adopt the USCRN triple temperature sensor configuration. NERON is also now configuring that network's precipitation gauge to be identical to the USCRN gauge. NERON will also use the identical temperature sensor. Finally, NERON will use the USCRN calibration facility and procedures to verify and correct instrumentation prior to field deployment. This integration effort is now cross-matrixed among three NOAA Line Offices, NESDIS, NWS, and OAR.

4.4.1 FY2005 Precipitation Testing Results

Two USCRN precipitation testbeds are located at Sterling, VA and Johnstown, PA.   Most of the new development engineering and testing undertaken by the USCRN program uses these two NOAA facilities. The facilities allow sufficient room and controlled monitoring to test numerous precipitation gauges (weighing bucket, weighing spot, tipping bucket, etc.), other sensors, and large and small wind fences from a variety of NOAA networks.

Using controlled, multiple sensor data focused transfer functions are being developed separately for liquid and frozen precipitation measurement and control. These transfer functions are being developed for three non-CRN sensors of importance: the current ASOS precipitation gauge, the new ASOS precipitation gauge, and the new NERON rain gauge in FY2006. During FY2006 a new wind fence design for the USCRN rain gauge is scheduled to for testing that began in FY2005 and as part of examining a technology refresh a new precipitation gauge is also being evaluated.

Consensus was reached on the way the Geonor precipitation gauge measures precipitation in FY05. A meeting was held in April 2005 with the NWS, OAR, NESDIS and Meteorological Services of Canada. The direct result of this meeting was a USCRN Technical Note on the Official USCRN precipitation algorithm (see references)

. Some of the experiments underway at these testbed sites include:

- Preliminary testing of the USCRN Precipitation Algorithm.
- Installation of Double Alter shields to define operating characteristics with the DFIR and the SDFIR.
- Cross comparisons of primary gauges (Geonor and Ott) with the Tretyakov and Alter shields. For example, install an Ott gauge with the Alter shield and a Geonor with a Tretyakov shield. There is some question as to how the Alter and Tretyakov shields really function as compared to each other.
- Liquid precipitation events are fairly well understood with regard to gauge/shield functioning. Solid precipitation events need further refinement. Unfortunately, Johnstown and, especially, Sterling have relatively few solid events. Installation of test gauges in more severe climates in terms of temperature and wind would be very helpful. Suggested locations would be the upper Midwest, Canada, or Alaska.
- Additional gauge installations such as the Vaisala precipitation gauge should be ongoing as future gauge development may warrant.
- Continued evaluation of the "wetness sensor." This sensor is being backfitted to the USCRN commissioned field stations during their Annual Maintenance Visits. This activity should be completed during FY2006.
- Continued collection of data from current gauges and test sites to increase the number of precipitation events so that the resulting statistics will be more robust.

FY2005 sensor testing and science studies included refinements to existing instrumentation such as testing of wetness sensors, raingauges, relative humidity sensors, meteor burst, and new raingauge shields In addition the Fall protection Device was installed at all sites. The FPD allows a valid precipitation measurement to still be made if one of the three sensors on the gauge fails.

4.4.2 FY2005 Temperature Testing Results

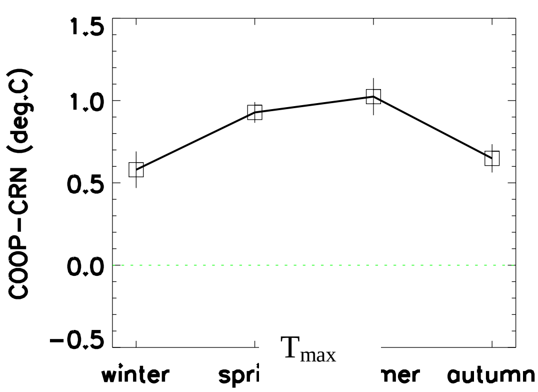
Temperature sensor testing for fitness, maintainability, calibration stability, cost, and precision have continued throughout FY2005. Data has been examined for errors, and replicable quantitative research papers have shown that the CRN platinum-resistance thermometers (PRT's) are of NIST grade. The CRN PRT's appear to be slightly more precise and stable than the calibration instruments used as controls.

CRN temperature instruments have also been tested against temperature sensors used by ASOS and COOP. These studies have quantified specific errors and transfer functions among all three instruments as below:

- Preliminary analyses of the difference between temperature observations recorded by COOP/ASOS and USCRN systems.

  - ASOS vs. USCRN
    (1) Local effect can complicate the co-located comparison as the temperature difference between the instruments depends not only on local heating/cooling, but is strongly modified by other weather parameters, such as cloudiness, wind, and solar radiation

  - COOP vs. USCRN
    (1) An annual warming of 0.83C occurs in COOP T_{max}, and an annual cooling of 0.03C is shown in COOP T_{min}.



- Estimation of normals for USCRN stations

  Normals of temperature and precipitation have been estimated for USCRN stations by using USCRN measurements and measurements from COOP network. To seek the best normal estimation, several variations on estimation techniques were evaluated.

USCRN estimated normals products, including values of normals, error bars, and relative magnitudes of errors compared to typical monthly anomalies have been generated and are ready for use in applications of climate monitoring and other areas.

Estimation of Composite Station (CS) time series for USCRN stations. The goal of this work is to create artificial time series of mean monthly T_{min}, T_{max}, and T_{mea}, and mean monthly precipitation for USCRN stations that go back in time to the start of reliable observations in the area. Tests are being conducted, trying to find the approach that the time series to be generated can most accurately reflect the long term (decadal- to century-scale) climate variability and trend in the region as well as the local scale variability. This work is under way.

Errors in estimated Jan. Tmin normal

Two years of measurements have shown that USCRN temperature sensors are interchangeable and more accurate than the standard or baseline controls that they were being compared to.

4.5 FY 2005 Integration with the Modernized COOP Program (NERON)

The USCRN sensor baseline studies and network sensor intercomparisons (Secs. 4.4.1 and 4.4.2) have laid the path open for possible robust network integrations in the near future. For instance, a network complementary to the USCRN, the US Historical Climate Network (USHCN), was identified, documented and has been essential to much scientific research. Modernization of about 1000 HCN sites will establish confidence in the detection of regional climate trends of 95%+ for precipitation and 98%+ for temperature.

The two NOAA nets (USCRN and NERON) are complementary, but not redundant. Differences of level of activity, station siting, instrument redundancy, and observational precision exist between the two networks. Logistics train, maintenance needs, end data uses and user communities are similar. Despite these differences close integration of the USCRN and NERON is in the best interest of corporate NOAA.

During FY2004 and FY2005 exchanges with NERON of information and technical data on USCRN sensors, communications, data ingest and archival, QA/QC, and management practices began. Starting in FY04Q3 exchange meetings involving USCRN and NERON personnel were held to search for common missions, goals, and implementation practices. All USCRN manuals, handbooks, guidelines, and other documentation developed over the past several years were transferred to the NERON Program. The NERON program is adopting similar standards for measurements as the USCRN and is including their instrumentation suites in the USCRN test facilities. The USCRN precipitation gauge has been selected for deployment by the NERON.

There is considerable gain in modernizing the sites in the USHCN using CRN technologies. Continuity of climate applications with as long a period of homogeneous record as possible will be enabled. Since the operational data will be available in near-real time, climate applications and significance of climate events can be established and provided to users. This network will utilize the same infrastructure as the USCRN. The instrumentation, calibration, engineering and maintenance will be almost identical to the USCRN. This will allow for the more rapid development of transfer functions between the two. The measure of performance will be related to the improved confidence in detecting regional trends and variability for precipitation. This will also be possible for temperature, but precipitation is more difficult, so the performance measure will be based on precipitation. Data from co-located instruments supports and speeds temperature and precipitation transfer function developments. This leverages climate- quality observations to higher-density grids from which USCRN is resource-constrained. This co-location effort and transfer function activity can continue indefinitely.

4.6 FY 2005 International Cooperation

International interest in the USCRN and its technology continues to grow. USCRN high-quality environmental measurements have been proven in rigorous field tests and four years of field operations. International interest is now being more fiely focused upon adopting and adapting USCRN technologies, siting standards, data processing, and archival procedures.

The first nation to duplicate USCRN practices and technology is Canada. The USCRN was invited to have a U.S Representative on the Canadian Atmospheric Environment Service (AES) National Monitoring Change Management Board. This invitation was accepted. Likewise, a representative from the Canadian counterpart of the USCRN, the Canadian Reference Climate Network (RCN) program, participates in the activities and deliberations of the USCRN Ad Hoc Science Review Panel.

As a result of the FY2005 side-by-side testing and evaluation of the USCRN precipitation gauge, a decision has been made by the AES to incorporate the USCRN hardware architecture into the Canadian RCN.

During FY2004, a CRN station was deployed to the Canadian National Testbed Site (Egbert, Ontario). In early FY2006 a Canadian RCS station will be deployed to a U.S. Test Site. It is anticipated that once the Canadian RCS station is installed network transfer functions will be examined between the two networks starting in late FY2006. Such transfer function determinations between these two national nets would increase the geographic spatial area of homogeneous long-term climate observations over North America by >100%.

U.S./Canada discussions have included:

a. The role played by redundant temperature and precipitation sensors

b. Processing multiple observations into single temperature and precipitation values using standardized algorithms.

c. Field lessons learned such as experience in measuring solid precipitation

d. Detecting, reporting and tracking anomalous events for station maintenance

e. Installation, maintenance and inspection protocols

f. Using the Web to disseminate data and documentation

g. Quality control procedures

In addition to U.S. – Canada activities, USCRN stations have been selected for deployment in various environments on other continents where assistance in modernization is desired. Towards this end, during FY2005 two USCRN stations were configured to be GCOS test stations (high-elevation and high precipitation environment stations). These stations were deployed to two extreme Hawaiian environments as prototypes for future deployments in the Andes and elsewhere as GCOS takes actions to upgrade global baseline climate monitoring stations.

Discussions began in August-September 2005 to satisfy an initial interest in modernization and climate monitoring in Latin America by identifying with the National Meteorological service of Mexico specific station sites for possible forthcoming deployments of CRN stations at an astronomical observatory (high-elevation station) and in some Northern Mexico lower-elevation sites. The lowland sites in Mexico can be particularly important for allowing transfer functions to be established between the U.S. Southwestern CRN stations and those Mexican CRN stations that may be co-located with longer-period stations of the Mexican NMS. If successful, this would be a multi-year effort.

This initiative can also extend the areal coverage and increase the confidence level of older Mexican data for use in the North American Drought Monitor, an operational NCDC product that portrays drought conditions in all three countries of North America.

Additionally, during FY2006 the USCRN will be involved with the WMO and have a representative to the Expert Team on Surface-based Instrument Inter-comparisons and Calibration Methods (ET/SBII&CM). This will include participating in international intercomparisons of raingauges in Italy and France.

4.7 FY 2005 and FY2006 Station Deployments & Commissionings: Plans and Definitions

At the end of FY2004, 69 CRN stations were operating at 62 locations. <u>Only 56 of those 69 stations were commissioned field sites.</u> The remaining 13 (non-commissioned) stations were in burn-in phase (90 days of post-deployment site testing), or were set aside solely as engineering test sites (and were off-line - not on GOES DCS as the primary communication mode), or were deployments outside of the USCRN Performance Measure spatial grid (e.g., in Alaska and Canada). As a general rule, station commissioning usually follows station deployment after a burn-in (test) and certification period of 30-90 days.

The amalgamation of all CRN station into one apparent statistical class prior to FY2005 led to unintended confusion of the relationship between the base Performance Measures for USCRN and the number of USCRN stations. Therefore, in an effort to achieve greater clarity it should be understood that the USCRN PM is based upon ONLY upon the number of and the proper geographic location of those USCRN stations <u>that are commissioned field stations</u>. A list of those stations and their locations is attached as Appendix B.

To clarify this possible misunderstanding, in late 2005 CRN personnel developed a more accurate station figure (using only **<u>“commissioned field stations in the CONUS” at USCRN locations</u>**) as the most accurate representation of the National PM for Climate Uncertainty.

Thus, there may be initial confusion during this transition period that, for instance, the FY2004 report listed that 69 CRN stations were deployed at the end of FY2004. That statement is true. On the other hand, this statement led to a misperception in that it was not clearly stated that only 56 of those 69 stations were used in calculation of the FY04 PM’s, and that the 69 stations were actually deployed at only 62 discrete locations.

Likewise for FY05 end-of-the-year reporting, we have a total of 82 CRN stations deployed. Only 76 of those were funded by USCRN; only 72 of these stations are sited at 65 locations IAW with the baseline USCRN CONUS deployment grid guidelines:

a. two stations (82 & 81) were funded by a State of Alabama earmark (unfortunately both of these stations were deployed in specific counties, and were not on the USCRN PM grid);

b. another two stations (80 &79) were deployed to Alaska using FY2005 GCOS funding for densification of high-latitude data inputs as satisfying a NOAA element for the forthcoming International Polar Year;

c. two other stations were deployed in Hawaii as FY2005 GCOS extreme environment test sites (high-altitude and tropical closed forest ecotones – 78 & 77). These Hawaiian test sites provide readily accessible U.S.-controlled locations prior to the probability of CRN stations being adopted by other nations for deployments in their mountain ranges and heavy precipitation areas. If there are problems in these stations' functionality in these extreme environments, these problems can be addressed prior to be installed internationally.

d. four other stations (76-73) were also not included in the FY2005 PM calculation due to restricted functionality or geographic fitness as fully commissionable USCRN field stations in the CONUS. These four sites are:

    i. 76 & 75 were two Alaskan stations deployed in FY2001 as early CRN test sites for Alaskan extreme environmental conditions – neither of those stations should be used in calculation of the CONUS PM, but they may be integrated into any forthcoming Alaskan CRN network as supplementary sites for that area.

    ii. 74 & 73 are the U.S. CONUS primary engineering test sites at Johnstown, PA and Sterling, VA. Data from neither of these two sites is presently is available via GOES-DCS. Likewise neither of these two sites has had a site survey, a site panel review, nor a Site License Agreement (likely not technically necessary as they are located at NOAA-owned or leased engineering facilities).

Thus, only 72 USCRN stations at 65 locations should be used in calculating the end-of-the year FY2005 Performance Measures. Yet it is true that there are, at this time, 82 CRN stations. Input calculation of the USCRN CONUS PM's from the ten stations identified above is not statistically proper as the data from each of those ten stations is either off the USCRN CONUS grid or it is reserved as emanating from experimental/test sites whose configuration is not static).

For FY2006, with the addition of more GCOS sites outside the CONUS, the apparent discrepancy between the total number of CRN sites and the number of USCRN sites used in calculation of the USCRN PM's will increase. An early estimate is that 4 GCOS sites may be deployed in FY2006. All will be outside the CONUS.

There are precisely 15 USCRN sites scheduled for deployment in the CONUS in FY2006. There are no USCRN-funded sites scheduled for deployment outside the CONUS as of this time - nor are any special-purpose stations (e.g., test sites) scheduled for deployment during FY2006. There may well be additional stations deployed during FY2006 from unplanned external funds, so the potential for end-of-year FY2006 confusion may once again exist.

The Station Locations listing in Appendix B is the most accurate current listing of all CRN Locations to be used in Performance Measure Estimation for FY2005 through FY2008. Any changes that may take place are envisioned as minor geographically.

5. Summary

The Climate Reference network has achieved the initial goals and performance measures that were developed at the program's inception. The FY2005 budget hiatus is viewed as an anomaly. Although the FY2005 budget situation resulted in a deployment phase stretch-out into FY2008, the integrity of the USCRN network and of its data remains at the highest level.

Stations have been established on schedule and maintained with reliability. The USCRN is already starting to provide the United States with a first-class climate and environmental monitoring network that meets national needs, and meets international commitments to monitor and document climate change. The Climate Reference Network will help fill an important land-based gap in U.S. climate data. These data are needed in a larger and more comprehensive Earth observation system being developed by more than 34 countries.

6. FY2006 Planned Activities and Goals

Research and engineering development activities envisioned for FY2006 focus and resources include:

a. Transfer Function determinations inter-network. This first priority is to determine the transfer functions between the USCRN and the Cooperative Network. Other networks being considered for transfer function determinations include ASOS, NERON, and as far as possible – non-NOAA networks such RAWS, SCAN, SNOTEL, and selected State mesonets.

b. Derivation of Pseudo-normals once transfer functions are established. This work must be approached with great care and critical review.

c. Exercising the capability and fitness of combinations of USCRN sensors providing ground truth points for NOAA satellite systems.

d. Testing and deployment of Wetness Sensors, an activity begun in FY04Q4. Wetness Sensors will be retrofitted to all USCRN and used to improve the precipitation measurements.

e. Acquisition, testing and possible deployment of Relative Humidity Sensors. If instruments considered are of sufficient precision, an RH sensor will be retrofitted to all USCRN stations.

f. Testing of Iridium or similar communications for harsh environs and two-way communication capabilities. The lessons of Hurricane Katrina (August 2005) strongly indicate that a two-way capability is essential for station tending when extreme weather events are present.

g. Deeper study of Health of the Network and Data Ingest percentages in order to identify seasonal biases, component failure patterns, and individual stations that lag in their performance and/or precision.

h. Closer interworking with and support for NERON and/or USHCN-M as that program evolves.

i. Coordinate with Canada on transfer functions between the Canadian RCS and the USCRN

j. Develop international ties on global standards and commonalities in the measurement of precipitation throughout the WMO community.

k. Initiate preliminary selection and assessment of soil moisture and temperature measurements for the USCRN.

Appendix A. Ten Climate Principles[1]

1. Management of Network Change: Assess how and the extent to which a proposed change could influence the existing and future climatology obtainable from the system, particularly with respect to climate variability and change. Changes in observing times will adversely affect time series. Without adequate transfer functions, spatial changes and spatially dependent changes will adversely affect the mapping of climate elements.

2. Parallel Testing: Operate the old system simultaneously with the replacement system over a sufficiently long time period to observe the behavior of the two systems over the full range of variation of the climate variable observed. This testing should allow the derivation of a transfer function to convert between climatic data taken before and after the change. When the observing system is of sufficient scope and importance, the results of parallel testing should be documented in peer-reviewed literature.

3. Metadata: Fully document each observing system and its operating procedures. This is particularly important immediately prior to and following any contemplated change. Relevant information includes: instruments, instrument sampling time, calibration, validation, station location, exposure, local environmental conditions, and other platform specifics that could influence the data history. The recording should be a mandatory part of the observing routine and should be archived with the original data. Algorithms used to process observations need proper documentation. Documentation of changes and improvements in the algorithms should be carried along with the data throughout the archiving process.

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

5. Integrated Environmental Assessment: Anticipate the use of the data in the development of environmental assessments, particularly those pertaining to climate variability and change, as part of a climate observing system's strategic plan. National climate assessments and international assessments, (e.g., international ozone or IPCC) are critical to evaluating and maintaining overall consistency of climate data sets. A system's participation in an integrated environmental monitoring program can also be quite beneficial for maintaining climate relevancy. Time series of data achieve value only with regular scientific analysis.

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

7. Complementary Data: Give the highest priority in the design and implementation of new sites or instruments within an observing system to data-poor regions, poorly observed variables, regions sensitive to change, and key measurements with inadequate temporal resolution. Data sets archived in non-electronic format should be converted for efficient electronic access.

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

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

10. Data and Metadata Access: Develop data management systems that facilitate access, use, and interpretation of the data and data products by users. Freedom of access, low cost mechanisms that facilitate use (directories, catalogs, browse capabilities, availability of metadata on station histories, algorithm accessibility and documentation, etc.), and quality control should be an integral part of data management. International cooperation is critical for successful data management.

[1] *Adequacy of Climate Observing Systems (NRC), National Academy of Sciences Press, Washington, D.C., 1999 (see pp. 17-18).*

Appendix B

Place Names and States of USCRN Station Final Locations
(Note: Colors are keyed to Figure 2 map)

Alabama
  - Gadsden
  - Mobile
  - Selma
- Arizona
  - Elgin
  - Grand Canyon
  - Petrified Forest
  - Tucson
  - Yuma
- Arkansas
  - Batesville
- California
  - Big Sur
  - Death Valley
  - Merced
  - Point Reyes
  - Redding
  - Redwoods
  - Santa Margarita
  - Yosemite
- Colorado
  - Boulder
  - Dinosaur
  - La Junta
  - Mesa Verde
  - Montrose
  - Nunn
- Florida
  - Big Cypress
  - Kennedy Space Center
  - Tampa
- Georgia
  - Brunswick
  - Newton
  - Watkinsville
- Idaho
  - Arco
  - Murphy
- Illinois
  - Champaign
  - Shabonna
- Indiana
  - Northern IN
- Iowa
  - Des Moines
- Kansas
  - Konza (Manhattan)
  - Smoky Valley
- Kentucky
  - Bowling Green
  - Versailles
- Louisiana
  - Lafayette
  - Monroe
- Maine
  - Limestone
  - Old Town
- Michigan
  - Chatham
  - Central MI
  - Sleeping Bear

- **Minnesota**
  - **Audubon**
  - **Goodrich**
  - **Grand Portage**
  - **Southern MN**
- **Mississippi**
  - **Blackville**
  - **Newton**
- **Missouri**
  - **Chillicothe**
  - **Shawnee Trail**
  - **White River**
- **Montana**
  - **Central MT**
  - **Lame Deer**
  - **St Mary**
  - **Western MT**
  - **Wolf Point**
- **Nebraska**
  - **Harrison**
  - **Lincoln**
  - **Whitman**
- **Nevada**
  - **Baker**
  - **Mercury**
  - **Reno**
- **New Hampshire**
  - **Durham**
- **New Mexico**
  - **Jornada**
  - **Los Alamos**
  - **Socorro**
- **New York**
  - **Ithaca**
  - **Lower St. Lawrence**
  - **Millbrook**
- **North Carolina**
  - **Asheville**
  - **Durham**
  - **Hatteras**
- **North Dakota**
  - **Medora**
- **Ohio**
  - **Coshocton**
- **Oklahoma**
  - **Goodwell**
  - **Stillwater**
- **Oregon**
  - **Finley**
  - **Gold Beach**
  - **John Day**
  - **Riley**
- **Pennsylvania**
  - **State College**
  - **Stroud**
- **Rhode Island**
  - **Kingston**
- **South Carolina**
  - **Blackville**
  - **McClellanville**
- **South Dakota**
  - **Buffalo**
  - **Fort Pierre**
  - **Ordway**
  - **Sioux Falls**

Tennessee

  - **Crossville**
- **Texas**
  - **Aransas**
  - **Austin**
  - **Big Bend**
  - **Edinburg**
  - **Fort Chadbourne**
  - **Laredo**
  - **Monahans**

- Muleshoe
- Palestine

- **Utah**
  - **Capital Reef**
  - **Dugway**
- **Vermont**
  - **Champlain Valley**
- **Virginia**
  - **Cape Charles**
  - **Central VA**
- **Washington**
  - **Cheney**
  - **Darrington**
  - **Hanford**
  - **Olympics**
- **West Virginia**
  - **Elkins**
- **Wisconsin**
  - **Necedah**
- **Wyoming**
  - **Black Hills NF**
  - **Lander**
  - **Moose**

Appendix C

Relevant FY2005 Science Studies and Scientific Source Papers Relating to USCRN

Evaluation of the U.S. Climate Reference Network as an Operational example of climate monitoring principles. Michael R. Helfert, NOAA/NESDIS/NCDC, Asheville, NC; and C. B. Baker, D. S. Braun, R. Buckner, M. Changery, F. Evans, G. M. Goodge, M. Phillips, N. Rowan, and B. Sun.13th Symposium on Meteorological Measurements and Observations June 2005

Evaluation of a double-Alter wind shield using sonic anemometers. Tilden Meyers, NOAA/ARL, Oak Ridge, TN; and E. J. Dumas, M. E. Heuer, C. B. Baker, M. Hall, and W. Tim. 13th Symposium on Meteorological Measurements and Observations June 2005

Overview of the USCRN research program C. Bruce Baker, NOAA/NESDIS/NCDC, Asheville, NC; and T. P. Meyers, M. D. Gifford, and R. P. Hosker . 13th Symposium on Meteorological Observations and Instrumentation June 2005.

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Appendix D.

USCRN Data Ingest Performance Measure Percentages

Discussion:

Although the USCRN network average (98.8%) for the full Period-of-Record (POR) is outstanding, and above the minimum level recommended (98.0%) as an overall Network Performance Measure for operations, a USCRN target of 100.0% is both the operational target day-by-day as well as an unattainable, if not unrealistic, long-term target.

Therefore, the data and metadata from individual stations felt to be adequate (98-99.9%) or underperforming (those less than 98%) are examined in detail to identify diurnal, seasonal anomalies, trends or biases (microclimatic problems) or systemic or systematic engineering problems of a higher order priority. As these biases or shortcomings are identified, engineering upgrades and fixes are applied.

These fixes are captured by the Configuration Management tool of the Configuration Change tracking. Examples of such fixes, which are largely invisible to the data users, include datalogger heaters, better moisture seals, estimation of MTBF (mean time between failures) of small but important components such as anemometer bearings and lifetimes, power issues and backups, battery lifetime extensions and layering, persistent icing conditions in high-latitude and high-elevation stations, and a host of small and incremental improvements to the precipitation gauge over the past four years.

POR statistics on data ingest are also biased, particularly for the early FY2001-2002 prototype stations, by early startup data gaps. Although engineering improvements may have already been applied, the data gaps in the early POR will continue to contaminate (as a decreasing proportion) the longer-term POR, while not affecting the later portions of the POR (e.g., FY2003-2005).

Thus, two tables are presented in the Appendix to demonstrate the differentiation between early POR problems versus the higher performing data ingest percentages that follow the most recent engineering improvements. Critical to the increased data ingest percentages has been the network backfitting of a 32-month memory capability to the station dataloggers.

Table A.
Cumulative USCRN Individual Station and Network Transmission and Data Ingest Percentages,
Jan 1, 2000 – Sept 30, 2005

State	Location	Operational	max obs	archived	% ingested	|	% 1st hr	% 2nd hr	% 3rd hr	% delayed	% pda
AL	Gadsden	04/14/2005	4080	4063	99.6	-	85	3.5	1.6	9	0.9
AL	Selma	05/26/2005	3072	3060	99.6	-	87.5	3.6	1.9	7	0
AZ	Elgin	09/14/2002	21264	21254	100	-	91.5	1.8	0.8	4.9	1
AZ	Tucson	09/18/2002	21264	21220	99.8	-	87.5	3.4	1.3	6.5	1.3
CA	Merced	03/25/2004	13320	13308	99.9	-	90	3	1.5	5	0.5
CA	Redding	03/25/2003	21264	21257	100	-	90.9	2	1	4.8	1.3
CA	Stovepipe Wells	05/05/2004	12336	12238	99.2	-	89	4.2	1.5	4.9	0.4
CO	Boulder	09/29/2003	17592	17591	100	-	90.2	2.6	1.1	5.5	0.6
CO	Dinosaur	07/21/2004	10488	10467	99.8	-	86.7	5.2	1.5	5.9	0.6
CO	La Junta	08/03/2004	10176	10155	99.8	-	74	12.7	3.2	7	3
CO	Montrose	07/25/2004	10392	10379	99.9	-	87.1	5.3	1.4	6.1	0.1
CO	Nunn	07/06/2003	19632	19611	99.9	-	87	6.3	1.3	4.7	0.6
FL	Titusville	05/07/2005	3528	3501	99.2	-	67	15.3	8.1	9.6	0
GA	Brunswick	12/16/2004	6936	6905	99.6	-	85.4	6	2.4	6.2	0
GA	Newton	08/20/2002	21264	21249	99.9	-	87.7	1.9	1	4.5	4.9
GA	Newton	08/20/2002	21264	21244	99.9	-	91.6	1.8	0.9	4.7	1
GA	Watkinsville	04/30/2004	12456	12438	99.9	-	89.9	3.6	1.2	4.9	0.4
HI	Hilo	09/26/2005	120	91	75.8	-	54.9	2.2	1.1	41.8	0
HI	Mauna Loa	09/26/2005	120	92	76.7	-	55.4	1.1	1.1	42.4	0
IA	Des Moines	09/15/2004	9144	9101	99.5	-	88.6	3.8	1.3	6.4	0
ID	Arco	07/10/2003	19536	19511	99.9	-	91	2	0.9	4.1	1.9
ID	Murphy	06/29/2003	19800	19781	99.9	-	88.5	2	1.1	6.6	1.9
IL	Champaign	12/20/2002	21264	21253	99.9	-	90.9	2	0.8	4.9	1.4
IL	Shabbona	08/16/2003	18648	18623	99.9	-	91.9	1.8	0.8	4.7	0.8
KS	Manhattan	10/01/2003	17544	17538	100	-	90.3	2.9	1	4.8	1.1
KY	Bowling Green	05/19/2004	12000	11977	99.8	-	89.8	3	1.1	5.6	0.6
KY	Versailles	06/12/2003	20208	20195	99.9	-	89.3	2.4	1.4	5.5	1.4
LA	Lafayette	01/10/2003	21264	21256	100	-	90.7	1.9	0.8	4.7	1.8
LA	Monroe	01/15/2003	21264	21243	99.9	-	90.2	3.3	0.9	4.9	0.8
ME	Limestone	09/20/2002	21264	21258	100	-	91.8	1.8	0.8	4.8	0.9

ME	Old Town	09/13/2002	21264	21262	100	-	91.6	1.7	0.8	1.4	4.5
MI	Chatham	11/10/2004	7800	7780	99.7	-	89	3.8	1.6	5.6	0
MN	Goodridge	08/21/2003	18528	18494	99.8	-	81.2	8.4	1.2	5.4	3.8
MS	Newton	11/03/2002	21264	21251	99.9	-	90.7	2.7	0.8	4.6	1.1
MT	St. Mary	09/25/2003	17688	17686	100	-	89.2	2.3	1	4.8	2.7
MT	Wolf Point	12/20/2001	21264	21258	100	-	88.8	1.7	1.1	5.2	3.1
MT	Wolf Point	12/20/2001	21264	21264	100	-	90.1	1.5	1	4.7	2.6
NC	Asheville	11/14/2000	21264	21168	99.5	-	91	2	1.1	5.5	0.4
NC	Asheville	11/14/2000	21264	21230	99.8	-	90.5	1.8	1	5.8	0.9
ND	Medora	09/18/2004	9072	9058	99.8	-	85.7	5.2	1.7	6.5	0.9
NE	Harrison	08/27/2003	18384	18365	99.9	-	90.4	2.2	1	5	1.3
NE	Lincoln	01/14/2002	21264	21254	100	-	88.5	2.3	1.4	6.2	1.5
NE	Lincoln	01/14/2002	21264	21261	100	-	90.8	1.6	1	5.4	1.2
NE	Whitman	09/15/2004	9144	9144	100	-	84.4	5.5	2.2	6.1	1.8
NH	Durham	12/11/2001	21264	21244	99.9	-	85.5	3.1	1.6	4.5	5.2
NH	Durham	12/16/2001	21264	21261	100	-	89.7	3.9	1	4.9	0.5
NM	Los Alamos	07/31/2004	10248	10217	99.7	-	76.8	8.4	2.9	6	5.9
NM	Socorro	05/24/2003	20664	20643	99.9	-	91.7	2.1	0.9	4.6	0.8
NV	Baker	05/09/2004	12240	12223	99.9	-	88	4.4	1.5	5.7	0.4
NV	Mercury	03/28/2004	13248	13228	99.8	-	87	5	2.1	4.9	1
NY	Ithaca	10/27/2004	8136	8115	99.7	-	87.3	4	1.6	6.5	0.6
NY	Millbrook	11/01/2004	8016	7998	99.8	-	87.5	4.3	1.8	6.1	0.4
OK	Goodwell	02/27/2004	13968	13924	99.7	-	88.6	3.7	1.2	5.7	0.7
OK	Stillwater	03/15/2002	21264	21256	100	-	89.5	3.8	1.1	4.8	0.7
OK	Stillwater	03/15/2002	21264	21250	99.9	-	91.3	1.9	0.9	4.9	0.9
ON	Egbert	07/15/2004	10632	10599	99.7	-	88.4	4.2	1.3	6.1	0
OR	John Day	03/16/2004	13536	13532	100	-	88	2.9	1.3	4	3.7
OR	Riley	07/03/2003	19704	19701	100	-	89.3	2.1	1.1	4.5	3
RI	Kingston	12/16/2001	21264	20944	98.5	-	89.2	2.3	0.9	5	2.7
RI	Kingston	12/16/2001	21264	21259	100	-	91.3	2.1	0.9	4.7	0.9
SC	Blackville	07/03/2002	21264	21216	99.8	-	89.6	2.1	1.1	6.2	0.9
SC	McClellan-ville	08/08/2002	21264	21248	99.9	-	88.8	2.7	1.1	6.1	1.2
SD	Buffalo	09/21/2004	9000	8976	99.7	-	86.6	5.4	1.6	6	0.3
SD	Sioux Falls	09/25/2002	21264	21259	100	-	91.1	1.9	0.9	5.7	0.5
TN	Crossville	12/03/2004	7248	7227	99.7	-	86.1	4.1	2.2	6.6	1
TX	Edinburg	02/19/2004	14160	14132	99.8	-	90.8	2.9	1	4.9	0.4
TX	Monahans	05/21/2003	20736	20587	99.3	-	91.7	1.9	0.7	4.6	1.1
TX	Muleshoe	02/27/2004	13968	13938	99.8	-	86.8	4.7	1.6	6.7	0.2
TX	Palestine	05/25/2003	20640	20549	99.6	-	92.3	1.9	0.8	4.6	0.5

VA	Cape Charles	03/03/2004	13848	13792	99.6	-	91.1	2.7	1.2	4.8	0.1
WA	Darrington	04/03/2003	21264	21253	99.9	-	88	2.3	0.9	4.8	3.9
WI	Necedah	10/04/2004	8688	8662	99.7	-	88.5	4	1.3	6.2	0
WV	Elkins	11/17/2003	16416	16399	99.9	-	89.9	2.2	1	4.8	2.1
WY	Lander	07/03/2004	10920	10898	99.8	-	87.2	4.2	1.3	5.2	2.1
WY	Moose	07/01/2004	10968	10968	100	-	87.8	4.5	1.5	5.8	0.4
-	Totals	-	1219152	1217023	99.8	-	88.9	3	1.2	5.2	1.6

<u>Notes for Appendix C, Table A, above:</u>
Only those operational field stations in the Lower 48 States (CONUS) are included in this listing.

A new GOES antenna capable of transmitting through ice and snow is being backfitted to the network. It was first installed at those stations with extreme winter conditions. The prototype antennae were developed at Alaskan test sites. The results were remarkable - Point Barrow and Fairbanks data ingests increased in real-time from the 65-75% range to 99.9-100.0% from installation date. This antenna is being deployed first to CONUS sites that also have winter icing, and then backfitted to all stations over time. 2004-2005 winter icing events affecting satellite transmissions were recorded as far south as the USCRN commissioned field station near Brownsville, Texas, so no place on the CONUS network is felt to be potentially immune from these weather-related outages.

Solar panel improvements have resulted in fewer station power problems on those stations which operate using solar power.

The improved seals, GOES transmitters, and dataloggers installed on Southern State prolonged high-humidity commissioned field sites have resulted in no further intrusions of water into datalogger and other electronic boxes on the stations. This situation will continue to be monitored, however.

Table B. FY2005 USCRN Individual Station and Overall Network Data Ingest Percentages

USCRN Network Overall 99.9%

SITEID	STATE	LOCATION	VECTOR	NAME	PCT
04739E	AL	Gadsden	19 N	Sand Mountain Research / Extension (Northwest Pasture)	99.7
04A5F6	AL	Selma	13 WNW	Auburn University, Black Belt Research and Extension Center	99.8
012422	AZ	Elgin	5 S	Audubon (Appleton-Whittell Research Ranch)	100.0
013754	AZ	Tucson	11 W	Sonora Desert Museum	100.0
0026D8	CA	Merced	23 WSW	Kesterson Reservoir (US Bureau of Reclamation)	100.0
01745E	CA	Redding	12 WNW	Whiskeytown National Recreation Area (RAWS Site)	100.0
039258	CA	Stovepipe Wells	1 SW	Death Valley National Park (Stovepipe Wells Site)	98.8
02232C	CO	Boulder	14 W	Mountain Research Station INSTAAR Univ. of CO (Hills Mill)	100.0
03C224	CO	Dinosaur	2 E	Dinosaur National Monument (Hdq. Maintenance Site)	100.0
03E4C8	CO	La Junta	17 WSW	USDA Comanche National Grassland	100.0
03D152	CO	Montrose	11 ENE	Black Canyon of the Gunnison National Park (Vernal Mesa)	100.0
016728	CO	Nunn	7 NNE	Ag. Res. Svc. Central Plains Exp. Range (SGS LTER at CSU)	100.0
05E406	FL	Titusville	7 E	NASA Kennedy Space Center, SLF Mid-Field Site	99.4
04831A	GA	Brunswick	23 S	Cumberland Island National Seashore (Stafford Field)	99.6
02C0DE	GA	Newton	11 SW	Robert W. Woodruff Foundation (Ichauway-Dubignon Site)	100.0
02B64E	GA	Newton	8 W	Robert W. Woodruff Foundation (Ichauway-George Site)	99.9
03F7BE	GA	Watkinsville	5 SSE	USDA/ARS Watkinsville (Colham Ferry Site)	100.0
044604	IA	Des Moines	17 E	Neal Smith NWR (NOAA Station Site)	99.7
01D4A6	ID	Arco	17 SW	Craters of the Moon NM & Preserve (Headquarters Area)	100.0
01E13C	ID	Murphy	10 W	ARS NW Watershed Research Cntr. (Reynolds Creek Site)	100.0
03073A	IL	Champaign	9 SW	Univ. of Illinois (Bondville Environ. & Atmos. Resrch. Stn.)	100.0
03144C	IL	Shabbona	5 NNE	Northern Illinois Agronomy Research Center	100.0
0076A4	KS	Manhattan	6 SSW	Kansas State University (Konza Prairie Biological	100.0

				Station)	
02A538	KY	Bowling Green	21 NNE	Mammoth Cave National Park (Job Corps Site)	100.0
027350	KY	Versailles	3 NNW	University of Kentucky (Woodford County Site)	100.0
0152B2	LA	Lafayette	13 SE	University of Louisiana at Lafayette (Cade Farm)	100.0
0141C4	LA	Monroe	26 N	Upper Ouachita National Wildlife Refuge	99.8
02E632	ME	Limestone	4 NNW	Aroostook National Wildlife Ref. (Fire Training Area)	100.0
02D3A8	ME	Old Town	2 W	University of Maine (Rogers Farm Site)	100.0
041678	MI	Chatham	1 SE	Michigan State University (Upper Peninsula Experiment Station)	99.8
0321D6	MN	Goodridge	12 NNW	Agassiz National Wildlife Refuge (Maintenance Shop Site)	99.6
02F544	MS	Newton	5 ENE	Mississippi State University (Coastal Plain Exp. Station)	100.0
02305A	MT	St. Mary	1 SSW	Glacier National Park (St. Mary Site)	100.0
009556	MT	Wolf Point	29 ENE	Fort Peck Indian Res. (Poplar River Site)	100.0
00A0CC	MT	Wolf Point	34 NE	Fort Peck Indian Res. (Give Out Morgan Site)	100.0
0255BC	NC	Asheville	13 S	NC Mtn. Horticultural Crops Res. Ctr. (Backlund Site)	99.7
0246CA	NC	Asheville	8 SSW	North Carolina Arboretum (Bierbaum Site)	100.0
05C2EA	ND	Medora	7 E	Theodore Roosevelt National Park (Painted Canyon Site)	100.0
0216B6	NE	Harrison	20 SSE	Agate Fossil Beds National Monument (Visitor Center Site)	100.0
00B3BA	NE	Lincoln	11 SW	Audubon Society (Spring Creek Prairie Site)	100.0
00C52A	NE	Lincoln	8 ENE	University of Nebraska (Prairie Pines Site)	100.0
043094	NE	Whitman	5 ENE	Gudmundsen Sandhills Laboratory (Site 1)	100.0
034430	NH	Durham	2 N	University of New Hampshire (Kingman Farm Site)	100.0
0332A0	NH	Durham	2 SSW	University of New Hampshire (Thompson Farm Site)	100.0
05B47A	NM	Los Alamos	13 W	Valles Caldera National Preserve (Valle Grande Site)	99.9
01C7D0	NM	Socorro	20 N	Sevilleta National Wildlife Refuge (LTER Site)	100.0
03A7C2	NV	Baker	5 W	Great Basin National Park (Gravel Pit Site)	100.0
001342	NV	Mercury	3 SSW	Nevada Test Site (Desert Rock Meteorological Lab)	100.0
045572	NY	Ithaca	13 E	Cornell University (Harford Teaching & Research Center)	99.8
0460E8	NY	Millbrook	3 W	Institute of Ecosystem Studies (Environmental Monitoring Station)	99.8
03812E	OK	Goodwell	2 E	OK Panhandle Research & Extn. Center (Native Grassland Site)	100.0
00D65C	OK	Stillwater	2 W	Oklahoma State Univ. (Ag. Research Farm Site)	100.0
00E3C6	OK	Stillwater	5 WNW	Oklahoma State University (Efaw Farm Site)	99.9

0184DA	OR	John Day	35 WNW	John Day Fossil Beds Nat'l. Mon.(Sheep Rock Hdqs.)	100.0
01F24A	OR	Riley	10 WSW	Northern Great Basin Experimental Range (Rainout Site)	100.0
035746	RI	Kingston	1NW	University of Rhode Island (Plains Road Site)	100.0
0362DC	RI	Kingston	1W	University of Rhode Island (Peckham Farm Site)	99.9
0283D4	SC	Blackville	3W	Clemson University (Edisto Research & Edu. Ctr.)	99.8
0290A2	SC	McClellanville	7 NE	SCDNR (Santee Coastal Reserve)	99.9
05D19C	SD	Buffalo	13 ESE	SDSU Antelope Research Station (Calving Pasture Site)	100.0
0111B8	SD	Sioux Falls	14 NNE	EROS Data Center	100.0
04906C	TN	Crossville	7 NW	Univ. of Tennessee (Plateau Research and Education Center)	99.8
008620	TX	Edinburg	17 NNE	Lower Rio Grande Valley NWR (La Sal Del Rey)	100.0
01B140	TX	Monahans	6 ENE	(Sandhills State Park)	100.0
0371AA	TX	Muleshoe	19 S	Muleshoe National Wildlife Refuge (Headquarters Site)	100.0
01A236	TX	Palestine	6 WNW	NASA (National Scientific Balloon Facility)	99.3
04F58A	VA	Cape Charles	5 ENE	Anheuser Busch Coastal Res. Ctr. Univ. of VA (Oyster)	99.8
0197AC	WA	Darrington	21 NNE	North Cascades National Park (Marblemount)	99.9
0423E2	WI	Necedah	5 WNW	Necedah National Wildlife Refuge (Rynearson Dam No. 2)	99.8
0205C0	WV	Elkins	21 ENE	Canaan Valley Resort State Park (Cabins Area)	100.0
06138C	WY	Lander	11 SSE	Nature Conservancy (Red Canyon Ranch)	100.0
03B4B4	WY	Moose	1 NNE	Grand Teton National Park	100.0

Appendix E

Integration of Humidity Measurements into the U.S. Climate Reference Network

Atmospheric Water Vapor in Surface Layer (Why)

Water vapor is one of the most important variables of the atmosphere and high quality humidity measurements are essential for better understanding of the interactions between the atmosphere and the earth's surface. The importance of monitoring air humidity is widely associated with the hydrological cycle, land/ocean surface energy budget, biological environment including human animal adaptation, and substantial agriculture operations (water resource management, scientific irrigation decisions, plant evapotranspiration, water use efficiency, and plant photosynthesis). A knowledge of the spatial and temporal domains is important for understanding the global, regional, and micro scale processes. Without the air vapor water/humidity information, it is impossible for us to completely investigate the changes in atmosphere.

The source and the sink for almost all water in the atmosphere is the earth's surface, through evaporation and precipitation (Elliott, 1995). The complete hydrological cycle is characterizing in Figure 1. The hydrological cycle provides a model for understanding the global plumbing system. It is a closed system because water (or water vapor) is neither created nor destroyed. The evaporation and precipitation maintain the water balance from the global scale to the micro scale.

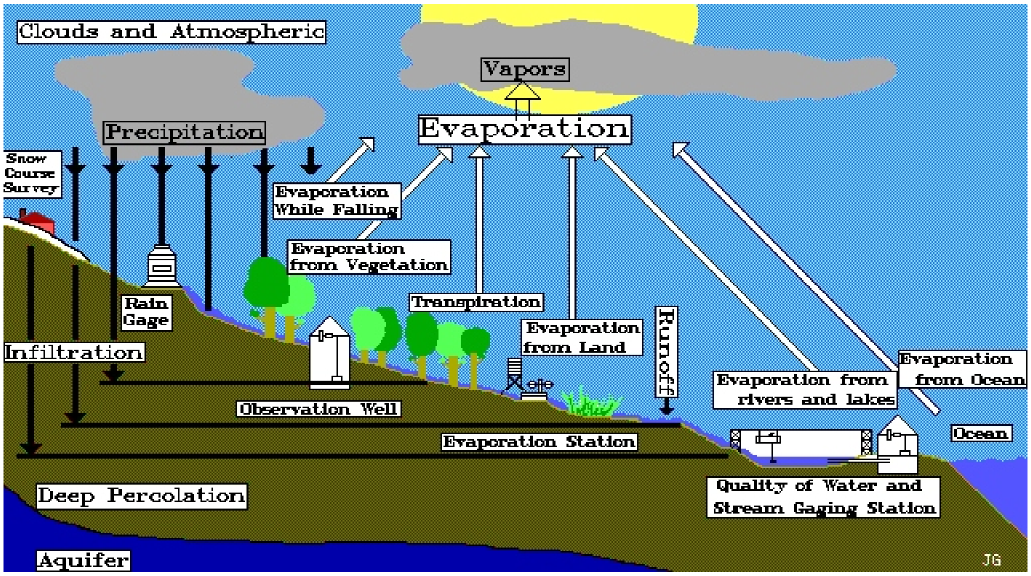

Fig 1. Scheme of Hydrological Cycle

The mechanism of precipitation formation involves phase change from water vapor to liquid or solid and the concurrent release of latent heat to the cloud systems. Thus, water vapor acts as a delivery mechanism in the redistribution of global energy. Water vapor determines the potential for evaporation and transpiration processes of the hydrological cycle (Figure 1).

Water vapor evaporated from the surface and moved about by atmospheric motions plays a very significant part in the atmosphere's energy budget because (1) latent energy taken up at the time of evaporation is carried wherever the water vapor is transported; (2) latent heat is released upon condensation and contributes to cloud buoyancy; and (3) the formation of clouds alter the radiation budget. A large portion of the energy transferred between the surface and free atmosphere is in the form of latent heat. The redistribution of this latent heat and its realization through condensation and precipitation is a main energy source for the general circulation (Elliott, 1995). The latent energy/heat (LE), which can only be monitored through humidity measurements, is a key component in the surface energy budget for global environmental issues and field water resource management issues. Changes in near-surface humidity will lead to changes in the evaporation and transpiration. This is critical to climate change because the net energy is partitioned between the sensible energy/heat (temperature dependent) and latent energy/heat (water vapor dependent). The accuracy and calibration of air humidity and solar radiation sensors are more critical than wind speed and air temperature in estimation of potential evapotranspiration (Meyer et al., 1986).

Many of the models used to estimate the effects of greenhouse gases portray an increasing water vapor concentration as the atmosphere warms, 20% to 30% in response to CO_2 doubling. This increase is expected if only because the saturation vapor pressure increases with temperature. Thus, if the relative humidity stays the same, the warmer air will hold more water vapor. The water vapor content in turn would increase the warming. This positive feedback of water vapor is one of the largest factors acting to amplify the effects of increased greenhouse gas concentrations (Elliott, 1995). Any trends in temperature translate to a trend in the potential for air to hold water vapor. Even for carbon balance or photosynthetic activities, the water vapor variable plays an important role (Rosenberg, 1983).

Water Vapor/Air Humidity Variables and Algorithms (What)

There are a number of variables that reflect the amount of water vapor in the air. As most depend in one fashion or another on the temperature of the parcel being considered, almost any measurement of a water vapor variable is accompanied by a measurement of temperature. The following symbols will be used in this section in discussing water vapor measurements.

> e e = Vapor pressure or partial pressure of vapor in air, millibars. e_i = Vapor pressure with respect to ice, millibars at T_f. e_w = Vapor pressure with respect to water, millibars at $T_{d.\,is}$, e_{ws} = Saturation vapor pressure with respect to ice (I) or water (w), millibars T = temperature, $^\circ$C T_a = Ambient or dry bulb temperature, $^\circ$C T_d = Dew point temperature, $^\circ$C T_f = Frost point temperature, $^\circ$C T_w = Wet bulb temperature, $^\circ$C P = total pressure of air, millibars f(p) = Enhancement factor RH = Relative humidity, % W = Mixing ratio

Atmospheric humidity refers to the water vapor content in air. Humidity measurements can be stated in a variety of terms and units. The commonly used terms are absolute humidity, relative humidity (RH), dew/frost point temperature, wet bulb temperature, and vapor pressure as well.

Absolute Humidity is defined as the water vapor density and is expressed as water vapor mass per unit volume of dry air. Absolute humidity can be expressed as follows,

$$\frac{g}{m^3}(absolute\_humidity) = \frac{216.7e_w}{T_a + 273.16} \qquad (1)$$

Therefore, it can be calculated from known RH and dry bulb temperature. In addition, the water vapor content can be expressed as parts per million by volume (ppm_v) (mixing ratio) or parts per million by weight (ppm_w).

Dew Point Temperature is defined as the temperature to which a given parcel of air must be cooled at constant pressure and constant water vapor content in order for saturation to occur. Since the saturation vapor pressure with respect to water is a function of temperature only, there exists a temperature T_d for which e_{ws} is equal to e_w. T_d is independent of the air temperature as long as the air remains unsaturated. The saturation vapor pressure with respect to water is (Buck, 1981),

$$e_{ws} = (1.0007 + 3.46 \times 10^{-6} P)6.1121e^{\frac{17.502T}{T+240.97}} \quad (2)$$

Note that there are other equations to calculate saturation water vapor pressure (See Appendix). To derive the dew point temperature from relative humidity, e_w is substituted for e_{ws} in Equation (2) where the resulting temperature is the dew point temperature (T_d).

Frost Point Temperature is defined as the temperature to which a volume of air must be cooled, such that it becomes saturated with respect to ice. The saturation vapor pressure with respect to ice requires a minor adjustment of the constants in Equation (2) as given by the following (Buck, 1981),

$$e_{is} = (1.0003 + 4.18 \times 10^{-6} P)6.1115e^{\frac{22.452T}{T+272.55}} \quad (3)$$

Therefore, similarly the frost point temperature can be derived from Equation (3) based on the relation of e_{is} and e_i.

Relative Humidity is defined as the ratio of the actual partial vapor pressure to the saturation vapor pressure of the air, multiplied with 100% at the ambient temperature. In percentage terms

$$RH = \frac{e}{e_{is}} \times 100\% \quad (4)$$

or

$$RH = \frac{e}{e_{ws}} \times 100\%$$

For the purposes of operational meteorology, relative humidity at temperatures below 0 ^{o}C is evaluated with respect to water [second equation in Equation (4)] (Simidchiev, 1986). Since the saturation vapor pressure e_{ws} is temperature dependent, relative humidity (RH) when expressed without the temperature is useful in a qualitative way. In scientific work, relative humidity must be treated according to whether water or ice process is present and the temperature effect must be included.

Wet Bulb Temperature, T_w, of moist air at a given pressure and air temperature is the temperature attained when the moist air is brought adiabatically to saturation by evaporation of water into the moist air. A relationship between wet bulb temperature T_w, dry bulb temperature T_d, and the humidity ratio W is as follows,

$$W = \frac{(2501 - 2.381T_w)W_w - (T_d - T_w)}{2501 + 1.805T_d - 4.186T_w} \quad (5)$$

where W_w is the humidity mixing ratio at T_w. In terms of vapor pressure the mixing ratio can be expressed as follows,

$$W = 0.62198 \times \frac{e_w}{P - e_w} \quad (6)$$

Equation 5 requires an iterative solution because the variables involving T_w can not be separated mathematically. Through Equations (1) to (6), we can readily convert from one humidity variable to another.

The commonly reported variable related to air humidity is either dew point temperature or relative humidity along with air temperature, but these humidity related variables are not always measured directly. Rather, they are often calculated from another variable based on the air temperature (e.g., from dew point to relative humidity, or from relative humidity to dew point temperature) (ASHRAE, 1993). The errors involved in the calculation or derivation (error propagation) are serious because air temperature error and air pressure difference are propagated to the derived variables (Appleman, 1964; Gates, 1994, Elliott and Gaffen, 1993; Yilmaz, 1997; Lin and Hubbard 2000; and Hubbard et al, 2001). This is most serious when air temperature is below zero (Dery and Stieglitz, 2001). Additionally, changes in processing algorithms can lead to subtle differences in calculated variables which could then appear as apparent climate changes (Elliott and Gaffen, 1993; Wade, 1994; Hubbard et al., 2001). It should be noted that the relative humidity at temperatures less than 0°C is evaluated with respect to water. The advantages of this algorithm are as follows,

.(1) Most hygrometers which are essentially responsive to the relative humidity indicate relative humidity with respect to water at all temperatures.
.(2) The surface fog at slightly below 0°C consists of water, or mainly of water.
.(3) Relative humidity greater than 100% would in general not be observed. This is particularly important in synoptic weather messages, since the atmosphere is often supersaturated with respect to ice at temperatures below 0 °C.

.(4) The majority of existing records of relative humidity at temperature below 0 °C are expressed on a basis of saturation with respect to water.

Water Vapor Measurements in Surface Observations (How)

The most important specifications for the atmospheric humidity measurements when selecting a humidity sensor are (WMO, 1996; Brown, 1997; Wiederhold, 1997a and 1997b; Hubbard, et al., 2001; Roveti, 2001):

Accuracy
Repeatability
Interchangeability
Long-term stability
Ability to recover from condensation
Resistance to chemical and physical contaminants
Size
Packaging
Cost effectiveness

Additional significant long–term factors are the costs associated with sensors replacement, field and lab calibrations, and the complexity and reliability of the signal conditioning and data acquisition circuitry.

The two basic types are fundamental (or primary) sensors and secondary sensors. Fundamental sensors are accurate and easy to understand, but typically very expensive. Secondary sensors, although easier to use, require a deeper knowledge of humidity for an understanding of their operating principles and how best to use them. All low-cost RH sensors are secondary sensors.

Fundamental sensors are based on well-defined thermodynamic principles, such as the condensation of water due to saturation or the mass of water contained in a volume of air. These physical properties do not require direct calibration. Examples include continuously controlled chilled mirror sensors, aspirated psychrometers, electrolytic sensors, and gravimetric instruments.

Secondary sensors are based on an observed property of a material that changes in response to humidity. They can be calibrated to correspond to either relative or absolute humidity. They respond to:

.(1) Change in length, e.g., of hair, plant fiber, or nylon, as in the extension hygrometer;
.(2) Change in weight, as in the absorption hygrometer;
.(3) Change in impedance or capacitance, as in many electronic hygrometers.
The general performance of humidity instrument are summarized in Table 1.

Table 1. Summaries of Current humidity instruments/sensors (Wiederhold, 1997)

Sensor Type	Class	Range		Typical Accuracy
Gravimetric	Fundamental	-50 to 100	°C	0.1 K dewpoint
Chilled mirror	Fundamental	-90 to 90	°C	0.2 K dewpoint
Electrolytic	Fundamental	1 to 2000	ppmv	5 % of reading ppmv
Psychrometer	Fundamental	5 to 95	%	2 % RH
Impedance	Secondary	-100 to 30	°C	2 to 4 K dewpoint
Polymer capacitive (RH sensor)	Secondary	2 to 100	%	2 to 5 % RH

The surface meteorological observation requirements for the air temperature and air humidity measurements (WMO, 1996) are given in Table 2. Two technologies associated with two types of air humidity sensors emerge for the automated weather station observations. One is the chilled mirror hygrometer (fundamental sensor), the other is the capacitive RH sensors (secondary sensors) (Table 1).

Table 2. Air humidity and temperature specifications required by WMO (WMO, 1996)

Variable	Range	Reported resolution	Mode of measurement	Required accuracy	Time Constant	Output Averaging time	Achievable operational accuracy
Dewpoint temperature	-60 to +35 °C	0.1 K	Instantaneous	+/- 0.5 K	20 secs	1 min	+/- 0.5 K
Relative Humidity	5 to 100 %	1 %	Instantaneous	+/- 3%	40 secs	1 min	+/- 3 to 5 %
Air temperature	-60 to +60 °C	0.1 K	Instantaneous	+/- 0.1 K	20 secs	1 min	+/- 0.2 K
Extremes of air temperature	-60 to +60 °C	0.1 K	Instantaneous	+/-0.5 K	20 secs	1 min	+/-0.2 K

The chilled mirror hygrometer is the most accurate, reliable, and fundamental hygrometer commercially available and is therefore widely used as a calibration standard. The principles of the chilled mirror hygrometer are illustrated in Fig. 2. The surface temperature of a small gold or rhodium-plated copper mirror is controlled by a thermoelectric cooler (heat pump). A high intensity light-emitting diode (LED) illuminates the mirror. The quantity of reflected light from the mirror surface is detected by a photo-transistor or optical detector. The temperature reading from the temperature sensor (usually a highly precise PRT sensor) embedded within the mirror surface is the dew point temperature when the a dew layer is maintained on the mirror surface. The advantages include:

.(1) Based on fundamental measurement principle, i.e., it does not require periodic re-calibration. It will maintain its accuracy for long periods of time and can be made traceable to national standards (NIST, NPL, etc.) (e.g., Edge Tech's hygrometer with two-year 1% stability guaranteed) .

.(2) Very high accuracy, typically up to ± 0.2°C or better of dew or frost point (e.g., hygrometers in General Eastern, Edge Tech, and Yankee Environmental Systems).

.(3) Excellent repeatability and NO hysteresis.

.(4) Very broad range, down to frost points of -40 °C and up to dew points of 50 °C.

.(5) Reasonable resistance to chemical and physical contaminants (depending on the mode of the hygrometer's operation).

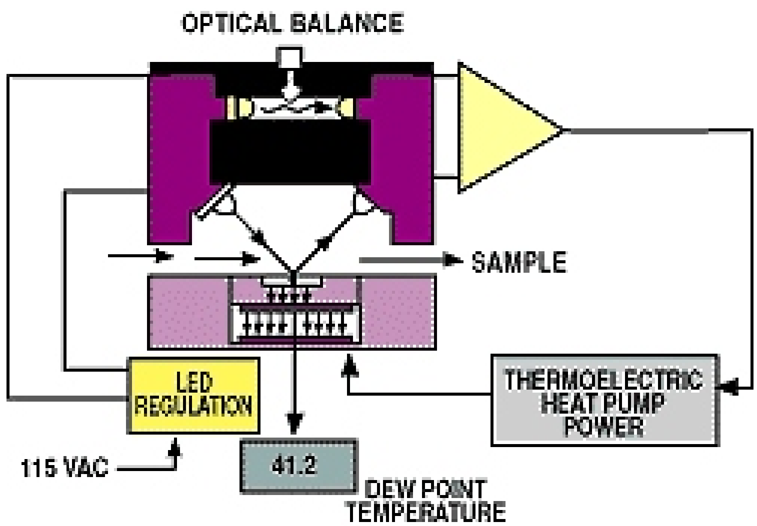

Fig 2. Schematic of chilled mirror

Its shortcomings have until recently been a sensitivity to contaminants that requires frequent maintenance, a slow response at very low frost points. Other drawbacks of the chilled mirror instrument are its expense relative to most other types and its higher maintenance demands skilled personnel, to properly monitor, and maintain an installation (e.g., providing proper air sample flow). The largest sources of error in a condensation hygrometer are the difficulty of accurately measuring the condensation surface temperature (Wiederhold, 1997a and Wiederhold, 2000) and accurately detecting the formation of condensation (even with some contaminants).

Up-to-date technology makes the chilled mirror hygrometer less sensitive to contaminants by improving optical circuits and control modes of the chilled mirror. For example, the automatic balance control (ABC) developed by Edge Tech (formerly EG & G or more formerly Cambridge Systems), the Programmable Automatic Contaminant Error Reduction (PACER techniques) developed by General Eastern Instruments, and Cycling Chilled Mirror Dew Point Hygrometer (CCM) (mirror is "dry" for 95% of the time and therefore contaminates at a much slower rate) developed by Protimeter.

Although these techniques greatly reduce the dew point temperature measurement errors caused by mirror contamination, the errors occurring at the mirror surface interface still contribute to the measurement errors, for example, **Kelvin effect** errors and **Raoult effect** errors (WMO, 1996; Wiederhold, 1997b). The greatest precision is obtained by controlling the mirror to a temperature (dew point) at which condensate neither accumulates nor dissipates, although, in practice, the above technologies will oscillate around this temperature. The response time of the mirror to heating and cooling is critical with respect to the amplitude of the oscillation, and should be of the order of one to two seconds. The air flow rate is also important for maintaining a stable deposit on the mirror. It is possible to determine the temperature at which condensation occurs with a precision of 0.05 K (WMO, 1996). On the other hand, the errors in temperature measurement in the hygrometer are unavoidable because of self heating, thermal conduction, and calibration limitations.

After more than a decade of experience with the chilled mirror in unattended humidity measurement, the National Weather Service ASOS program is considering the possibility of using another type of sensor. The technical maintenance of the chilled mirror sensor, although quite feasible in a research mode, has proven difficult over a widely dispersed network.

The capacitive polymer RH sensors are attractive for many applications due to their relatively low cost. State-of-the art techniques for producing capacitive sensors (Fig. 3) take advantage of many of the principles used in semiconductor manufacturing to yield sensors with minimal long-term drift and hysteresis. The polymer RH sensor acts as a capacitor dielectric with the interjected surface metal as electrodes and changes in dielectric constant as moisture is adsorbed or desorbed by the thin film. As the water molecule is highly polar, even small amounts of water can change the sensor capacitance to a measurable extent. In recent years, significant improvements have been made, and the current advantages of this type sensor are:

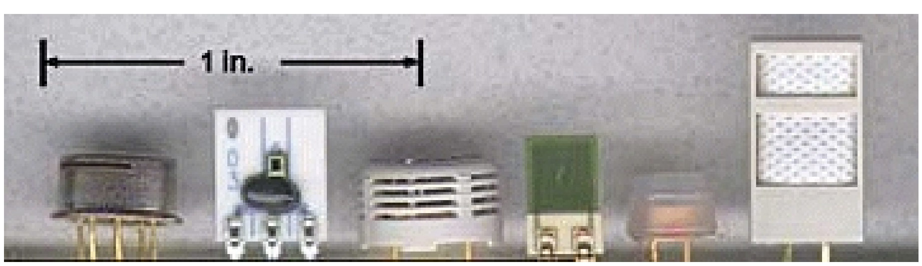

Fig 3. Samples of capacitive RH sensors

.(1) Far less temperature dependency compared to electric sensors (e.g. resistive sensors). If necessary, the sensor can be provided with electronic temperature compensation circuitry.

.(2) Fast response.

.(3) Virtually no hysteresis compared to earlier RH sensors.
.(4) Less frequent re-calibration or replacement.
.(5) Wide range available from 0.05% to 100%.
.(6) Very Good stability and Low cost, the accuracy can reach ±1% from the manufacturers (e.g., Vaisala capacitive RH sensors) with NIST traceable calibration.

The limitations of RH capacitive sensors include: sensitivity to certain contaminants; not useable in corrosive atmospheres; and slight temperature dependence. The last one is particularly important for long-term climate monitoring at wide ranges of both temperature and water vapor, especially in sub freezing conditions for higher humidity readings (close to 100%) (Clayton, et al, 1985; Anderson, 1994; Fleming, 1998; Hard, 1998; Dery and Stieglitz, 2001; Hubbard et al., 2001).

It should be noted that a simple statement of ±1% accuracy means little in terms of actual field performance because many variations are involved in the humidity measurements. For example, a sensor specified by the manufacturer to have an accuracy of ±1% may, after operating six months in the field, have an accuracy of ± 6% while another sensor, specified by the manufacturer at ±2%, could after 6 months in the same application have an accuracy ±3%. Therefore, the field testing is critical.

Procurement, Acquisition, Calibration and Installation of Relative Humidity Sensors for Integration into the Climate Reference Network

The following budget reflects the likely additional costs that will be incurred by ATDD for the procurement, calibration and installation of relative humidity sensors at USCRN stations. Note: this does NOT include the costs of modifying the data ingest and QA software at NCDC or elsewhere.

It is desired to maintain the calibration facility for all sensors used by USCRN at NOAA's Atmospheric Turbulence and Diffusion Division this maintains the integrity of the network by having a single calibration facility for all components of the CRN. In addition, the University of Nebraska will serve as a back-up calibration facility in the event there is a failure of the calibration equipment at ATDD. The University of Nebraska will play a major role in independent "field" calibrations or audits of deployed USCRN systems for both relative Humidity and Temperature to lend further credibility to the USCRN data set. This activity could include the continued evaluation of new sensors and technology that could be used in the USCRN program. A major objective of the USCRN design at the onset of the program was to make the system as modular as possible, to readily accommodate new sensor types, so no serious problems are expected in adding RH sensors to the existing instrument suite.

Following procurement of a traceable humidity calibration system, ATDD staff time will be required for the development and testing of an automated calibration procedure. The programming will be similar to that now used for the USCRN platinum resistance thermometers (PRTs). Cabling, packaging, and mounting of the RH sensors for field deployment are also expected to be rather similar to those required for the PRTs, and so will require only a modest cost per sensor.

Recommendations for CRN Humidity Measurements

Based on our tests and field trials we recommend that the humidity measurement be taken under aspirated conditions by using the CRN aspirated radiation shield. We also suggest that chilled mirror type sensors not be used because the frequent need for cleaning is not compatible with the remote field conditions common to CRN sites.

Recommendation for Humid Sites

We recommend the Vaisala 243 for the measurement of humidity. When the relative humidity exceeds 80% (when ambient temperature >0), the Vaisala 243 activates a heating element. This ensures that the sensor does not become 'wet' and give false saturation readings due to the long drying times following high humidities. The dew point measurement is taken at the elevated temperature with the concurrent reading from the capacitor. Our research trials indicate that this sensor can achieve ± 0.2C accuracy on dewpoint in the field at the 95% confidence level when compared to a field standard (DewTrack Meteorological Humidity System). The humidity error associated with the dewpoint reading is dependant upon the dry bulb temperature, the dewpoint depression and the propagation of errors from both temperature and dewpoint sensors. The range of errors is from 1 to about 6%. This sensor can output the relative humidity and dewpoint.

Calibration and Maintenance

These sensors require annual recalibration. We recommend a calibration using 25 set-points (5 for temperature from 0 to 50C and 5 for humidity from 10 to 95%) in the Thunder Scientific Humidity Calibrator. The new calibration equation is expected to be non-linear but, of a form suitable for direct incorporation into the data logger which will interface with the sensor. In addition, the humicap element would be heat cycled every two years to oxidize any material deposited on the face of the sensors.

Unit Cost

Vaisala 243	$2,600

Estimated USCRN RH Calibration and Deployment Costs

Procurement of Humidity Calibration system (**OSD**)	$30,000
Procurement of 20 RH sensors ($ 2185/ sensor) (**ATDD)**	$43,700
Automated RH calibration software (**ATDD)**	$2,500

Calibration of 20 RH sensors ($200/sensor) (**HPRCC**) $4,000

Installation of 20 RH sensors ($50 per sensor) (**ATDD)** $1,000

Budget discussion:
OSD will buy the RH Calibrator with ground system money.

There is a 90 day delivery on the RH calibrator so to expedite the deployment of the RH sensors the first group of sensors will be calibrated by HPRCC and test procedures will be finalized for the CRN.

Deploy of RH sensors would be accomplished on new installs and annual maintenance visits beginning late August 2004.

Review of the Draft Work Statement for Calibration and Installation of RH sensors for USCRN

1. What is the primary humidity variable that the USCRN should decide to monitor at the site? Is it RH or Dew point temperature? The HMP233 directly measures RH but the HMP243 directly measures the dew point which requires pressure (or elevation) corrections when describing global or regional air humidity. However, the topoclimatology of some sights results in high humidity for long durations. The HMP243 is designed to perform in such conditions while the HMP233 is not.

Any conversion between RH and dew point will certainly produce uncertainties ranged from ± 0.4 to ±6.6% RH (assuming inaccuracies: ± 0.2 ^{o}C Ta and ± 0.3 Td) or from ± 0.4 to 3.3 ^{o}C Td (assuming inaccuracies: ± 0.2 ^{o}C Ta and ± 2% RH). Improving the accuracies of measured variables is an effective approach to reduce these conversion uncertainties.

	Variable	Humicap Model	Power	Base Cost	Mfc's accuracy *	Field accuracy ***
HMP45	**RH**	**180**	**12V DC**	**$595**	**1% to 3%**	**5 to 7%**
HMP233	**RH**	**K**	**24V DC**	**$1175**	**1% to 2%**	**4 to 5 %**
HMP243	**Td**	**Composite KC**	**24V DC**	**$2185**	**0.1 to 0.3 ^{o}C ****	**0.2 ^{o}C**

*: Refers to the accuracies at specific temperature (e.g. 20^{o}C) (95% confidence level, k= 2).
**: Within the dew point range +/- 40ºC and less than 20ºC dew point depression.
***: Refer to yearlong field comparison results (hourly data, tested in Lincoln, NE, 95% confidence level).

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Appendix

Algorithms of Water Vapor Pressure

1. WMO Calculation (1996)
2. Industrial Applications (Wiederhold, 1997)
3. Buck's Equations (Buck, 1981)

$$e_{ws} = (1.0016 + 3.15 \times 10^{-6} P - 0.074 P^{-1}) 6.112 e^{\frac{17.62T}{T+243.12}}$$

$$e_{is} = (1.0003 + 4.18 \times 10^{-6} P) 6.1115 e^{\frac{22.452T}{T+272.55}}$$

$$e_{ws} = (1.00072 + 3.2 \times 10^{-6} P + 5.9 \times 10^{-10} PT) 6.1121 e^{\frac{(18.729 - \frac{T}{227.3})T}{T+257.87}}$$

$$e_{is} = (1.0003 + 4.18 \times 10^{-6} P) 6.1115 e^{\frac{(23.036 - \frac{T}{333.7})T}{T+279.82}}$$

---modifications of formula from Magnus (1844), Tetens (1930), Murray (1967). Also it was applied in the conversion between the RH and dewpoint in the LI-610 Dew Point Generator (LI-COR, Inc)

$$e_{ws} = (1.0007 + 3.46 \times 10^{-6} P)6.1121e^{\frac{17.502T}{T+240.97}}$$

$$e_{is} = (1.0016 + 3.15 \times 10^{-6} P - 0.074P^{-1})6.112e^{\frac{22.46T}{T+272.62}}$$