US Climate Reference Network

Annual Report for Fiscal Year 2018

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Cover Photo:
Photo of the new USCRN station in Bethel, Alaska; installed in August 2018. (Credit – Mark Hall)

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Report will be posted on the USCRN Website at

http://www.ncdc.noaa.gov/crn/annual-reports.html

Many thanks to the USCRN Team members for their invaluable assistance in aiding in the preparation of this report and for their many contributions during FY18:

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Preface and Introduction

During Fiscal Year 2018, the U.S. Climate Reference Network (USCRN) continued to make significant progress under the auspices of NOAA's Atmospheric Turbulence and Diffusion Division (ATDD) with cooperation and collaboration from NOAA's National Centers for Environmental Information (NCEI). The network consists of 114 stations across the conterminous 48 states, 22 stations in Alaska, 2 additional stations in Hawaii, and 2 at international test sites in Canada and Russia. Stations are installed in open (where possible), rural locations very likely to have stable land cover/use conditions for several decades to come.

At each site a suite of meteorological parameters are monitored, including triple redundancy for the primary temperature and precipitation variables, and for soil moisture and soil temperature. Instrumentation is regularly calibrated to National Institute for Standards and Technology (NIST) standards and maintained by a staff of expert engineers. This attention to detail in USCRN is intended to ensure the creation of an unimpeachable record of changes in surface climate over the United States for decades to come. Data are made available without restriction for all public, private, and government use. This section describes the rationale for the USCRN, its implementation, and some of the highlights of the first decade of operations.

Long-term, high-accuracy, stable environmental observations are essential to define the state of the global integrated Earth system, its history, and its future variability and change. Scientifically acceptable observations for climate analyses include: (1) operational weather observations when appropriate care in collection and archival methodologies has been exercised to establish sufficiently high accuracy for climate purposes; (2) limited-duration observations collected as part of research investigations to elucidate chemical, dynamical, biological, or radiative processes that contribute to maintaining climate patterns or to their variability; (3) high-accuracy, high-precision observations to document decadal-to-centennial changes; and (4) observations of well-recognized and scientifically acceptable climate proxies which are non-instrumental but nevertheless sufficiently controlled as to ensure numerical high-precision values that are scientifically valid.

The USCRN continues to fulfill this need for obtaining long-term sustainable and robust climate observations that are necessary to document long-term climate change trends for the United States. Beginning in 2009, the USCRN effort in the U.S. began expanding into the State of Alaska, and operating this climate observing network in an Arctic environment presents some unique challenges. There are currently a total of 22 operational USCRN stations (20 commissioned) in Alaska, with an eventual goal of having 29 commissioned stations by 2022.
Operating an automated climate quality observing network in the harsh and remote environment that exists at many sites in Alaska presents some unique problems related to station power, access to the station, and continued transmission of data. One critical use of these observations is as an independent data source to verify the existing U.S. temperature record derived from networks corrected for non-homogenous histories. These records can now be compared on the web site, and are found to agree well. Constructive feedback from end-users will allow for continued improvement of USCRN in the future and ensure that it continues to meet stakeholder requirements for precise climate measurements.

Highlights for FY2018

1. **Continuing to Push past the Halfway point in Alaska**
   In FY18, one new station was installed in Alaska (a) on Eyak Native Corporation property in Cordova, AK, in the southeast portion of the state. This brings the network configuration in the state up to 22 out of a planned total of 29 stations by FY2022.

2. **New Satellite Backup System Implemented**
   Early in 2018 USCRN was notified that Domestic Satellite (DOMSAT) system was scheduled to be discontinued on May 14, 2019. As a result, plans were made to replace the existing DOMSAT satellite dish, receiver and converter appliance at NCEI with an LRIT/HRIT compatible system. The HRIT (High Rate Information Transmission) broadcast is provided from the GOES satellites and carries the DCS data stream among many other data types; and this was successfully completed well in advance (at the end of FY18) of the decommissioning of the DOMSAT in May 2019.

3. **Software and Data System Improvements**
   Dramatic improvements in the performance of the USCRN database, and their associated web-based data and information access tools were made during the past year. The software development team worked closely with NCEI's database administrators to test and evaluate new database schemas and methods for improving performance.

4. **Science and Development Activities**
   The USCRN Climate Science Team made substantial process in its primary goal of improving the utility of soil moisture observations through standardization. The base standardized soil moisture dataset has been revised and published, and has begun the NCEI approval process. In the meantime work is progressing on using the standardized soil moisture data to better characterize drought in the U.S. through developing innovative indices. The expansion of the standardization work to other soil moisture sources such as satellite remotely sensed estimates is also underway.

5. **New Gridded Data for USCRN**
   To address a need for an enhanced utilization of the USCRN dataset, a gridded product was produced. Work begun in 2017 on developing daily means of more than 20 variables were computed, going back to at least 2006. In 2018, work to expand the use of USCRN soil moisture in gridded product development has continuing in earnest. Plans are underway to obtain detailed site-specific soil property information across all the USCRN stations to improve soil moisture measurements and fine tune gridded model predictions of soil moisture.

The remainder of the report will cover progress and activities in the following areas:

- Operational Activities in Alaska
- Operational Activities in the Conterminous U.S.
- Projects to Improve Data Processing, Monitoring, Data Access, and Product Quality
- USCRN Science and Development Activities
- Field and Testbed, and Monitoring Activities
- Development of Gridded USCRN Data
- Soil Sensor Testing and Evaluation

- Plans for FY2019

FY2018 Operational Activities in Alaska

Site Surveys: With the completion of the USCRN site survey program in FY2016, the work from that last survey was evaluated and the final three candidate station locations were selected in Aniak, Aleknagik, and St. Michael, in the western portion of the state (Figure 1). This will give the program a way forward to complete the installation of the final 8 stations by the end of FY2022.

Site Licenses Signed: No site license agreements were completed in FY 2018, but several are in progress.

Stations Installed: One new station (Bethel) was installed in Alaska in FY 2018.

Stations Commissioned: Two stations (Cordova and Toolik Lake) were commissioned in Alaska in FY 2018.

In addition to the station installed in FY 2018 at Bethel, three additional sites are licensed and pending installation (Kodiak, Galena, and Huslia). Licenses are pending from the Alaska Department of Natural Resources at Salmon Lake, Alaska Department of Natural Resources at Pumice Creek, Alaska North Slope Borough at Kaktovik, US Air Force site at Fort Yukon, Alaska Department of Transportation at St. Michael, Federal Aviation Administration at Aniak and Aleknagik Airport.

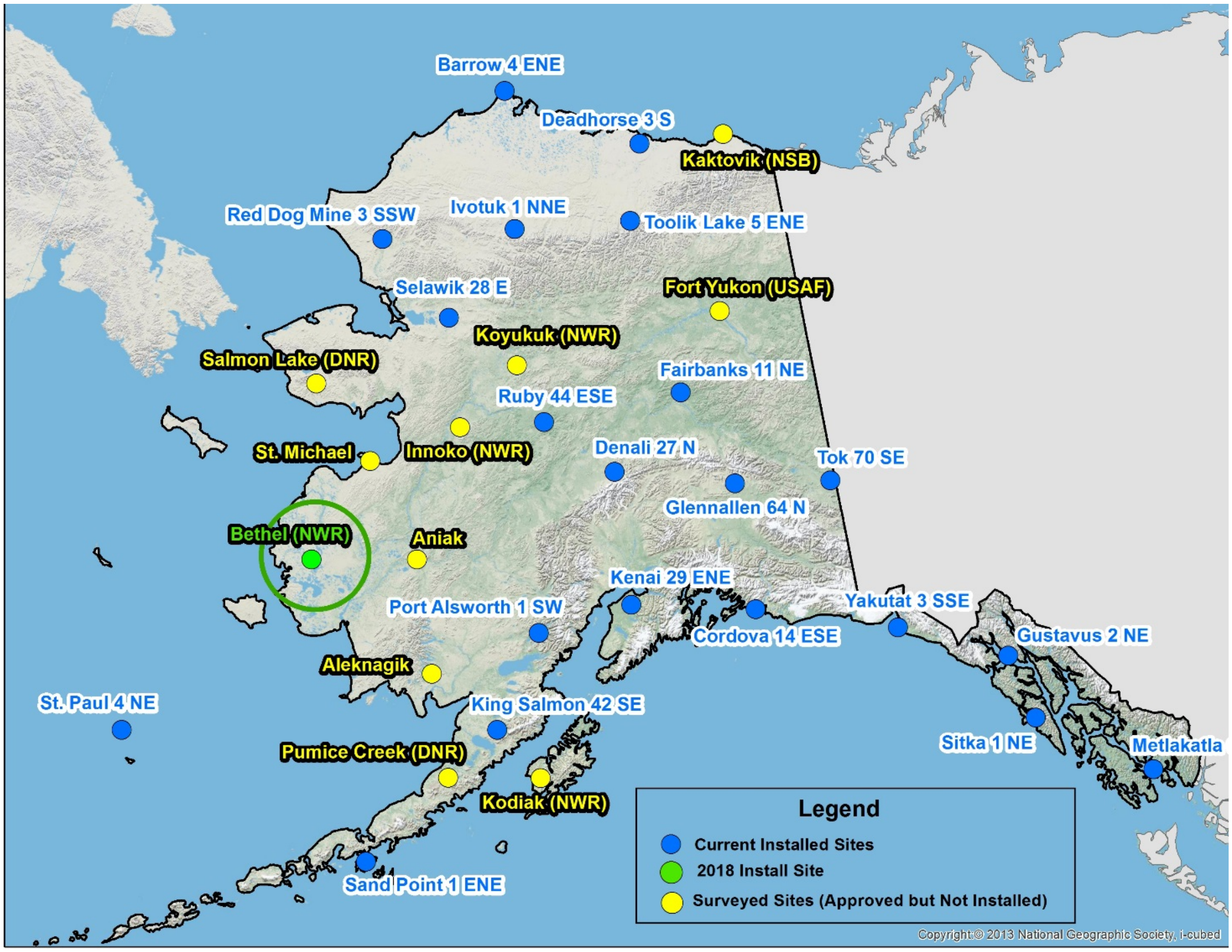


Figure 1. The map of USCRN stations in Alaska – existing and planned sites.

Table 1. USCRN in Alaska Reduction in Climate Uncertainty

FY	Sites Commissioned	Temperature Confidence	Precipitation Confidence
2010	2	59.0%	58.9%
2011	4	62.9%	62.7%
2012	5	64.4%	64.2%
2013	12	72.6%	72.4%
2014	13	73.4%	73.1%
2015	16	76.7%	76.0%
2016	18	79.1%	78.6%
2017	19	79.9%	79.3%
2018	21	82.3%	81.9%

Table 2. USCRN in Alaska Data Receipt Rates (%) for FY2018 by Quarter[1]

	Within 30 days	As of 9/30/18
Q1	94.3	95.0
Q2	93.3	94.1
Q3	99.7	99.9
Q4	97.7	99.9
Total	**97.2**	**97.3**

Table 3. FY2018 USCRN in Alaska Station Status

Station	Licensed	Installed	Commissioned
Barrow (NOAA Earth Systems Res. Lab.)	4/27/2001	08/2002	07/2013
Fairbanks (NOAA/NESDIS(FCDAS))	7/23/2002	08/2002	07/2013
St. Paul (NOAA NWS)	6/10/2005	08/2005	07/2013
Sitka (USGS)	6/15/2005	08/2005	07/2013
Sand Point (USGS)	02/12/2009	08/2009	09/2010
Port Alsworth (Lake Clark NPS)	09/09/2009	09/2009	09/2010
Red Dog Mine (NANA Regional Corp.)	07/13/2010	08/2010	09/2011
Kenai (Kenai NWR)	07/13/2010	08/2010	09/2011
Tok (Tetlin NWR)	07/13/2010	09/2011	09/2012
Gustavus (near Glacier Bay NP)	06/27/2011	09/2011	07/2013
King Salmon (Katmai NP)	06/20/2011	08/2012	07/2013
Metlakatla (Annette Island WSO)	03/27/2012	07/2012	07/2013
Glennallen (BLM)	06/11/2012	08/2013	07/2014
Deadhorse (Dept. of Natural Resources)	05/07/2014	06/2014	09/2015
Ivotuk (Arctic Slope Regional Corp.)	05/07/2014	06/2014	9/2015
Ruby (Nowitna NWR)	05/29/2012	08/2014	9/2015
Selawik (Selawik NWR)	05/29/2012	08/2015	9/2016
Denali (Denali NP)	01/07/2015	08/2015	9/2016
Yakutat (Tongass USFS)	06/28/2016	08/2016	9/2017
Cordova (Eyak Corporation)	01/23/2013	07/2017	9/2018
Toolik Lake (BLM)	06/07/2017	08/2017	9/2018
Bethel (Yukon Delta NWR)	03/14/2017	08/2018	TBD
Huslia (Koyukuk NWR)	03/14/2017	TBD	TBD
Kodiak (Kodiak NWR)	03/14/2017	TBD	TBD
Galena (Innoko NWR)	03/14/2017	TBD	TBD
Fort Yukon (US Air Force)	Pending	TBD	TBD
Nome (Salmon Lake AKDNR)	Pending	TBD	TBD
Port Heiden (Pumice Creek AKDNR)	Pending	TBD	TBD
Kaktovik (North Slope Borough)	Pending	TBD	TBD
St. Michael (AKDOT)	Pending	TBD	TBD
Aniak (FAA)	Pending	TBD	TBD

[1] The overall data receipt rate for the entire USCRN (including the stations in Alaska) was 99.8% (see Table 4) which is above the performance measurement standard of 98% across the entire network.

Aleknagik (City)	Pending	TBD	TBD

FY2018 Operational Activities in the Conterminous U.S.

The USCRN Program continues to successfully meet the requirements of data delivery in the conterminous U.S. (Table 4).

Table 4. Overall USCRN Data Receipt Rates (%) for FY2018 by Quarter (including Alaska)

	Within 30 days	As of 9/30/18
Q1	99.2	99.9
Q2	99.4	99.7
Q3	99.8	99.9
Q4	99.5	99.5
Total	**99.4**	**99.6**

USCRN Data Processing, Monitoring, Access, and Product Systems

NOAA/NCEI continued to provide operation and maintenance of USCRN data ingest, quality assurance, monitoring, access, and product systems in FY18. As in past years, the program's two software developers did an outstanding job maintaining high uptime rates by providing systems monitoring on an ongoing basis and quick response to outages that periodically occurred due to various factors beyond their control. They did these things while addressing new requirements including quality control and processing improvements, providing data analysis to ATDD engineers and USCRN scientists, transitioning to a new satellite-based data acquisition system, and validating USCRN's Rolling-12 data stream.

Other Quality Control and Processing Improvements

Occasionally, equipment malfunctions or other issues cause data to be erroneous, even though the values fall within the range of acceptable values set within the preset quality control threshold limits. In such cases, the inaccurate measurements are not flagged by the automated quality control algorithms in the ingest software system. However, there is a process of steps, based on manual intervention, to flag these faulty data values. The proper flagging of the erroneous observations are deployed via the ingest software's "bad sensor list", and once deployed in real-time, are then implemented retroactively, and verified.

Additionally, efforts began in FY18 by the software developers to expedite the manual quality control process by providing a simple web interface, through which manual quality control issues can be documented and flags applied automatically. Along with these manual quality control features, numerous performance improvements are being made which allow multiple data files to be ingested and existing data to be refreshed simultaneously. Completion of this work is expected in FY19.

Also in FY18, developers identified and wrote scripts to analyze solar radiation differences at some Alaska dual-instrument sites, worked with engineers to determine the causes of the differences, identified other variables with related issues, prepared/archived a summary of the analysis/results, and deployed the necessary flagging. In addition, developers wrote scripts to identify problematic wind speed values, prepared analysis to explore the possibility of auto-flagging of these faulty values in the future, and began manually flagging major past issues at some stations.

Operational Quality Control Processes for Soil Moisture/Temperature Data
At most USCRN stations, measurements of soil temperature and soil moisture are made at five depths from 5 to 100 cm in three equally spaced locations surrounding the tower. The large number of sensors combined with the environment in which the sensors operate requires continued attention by software developers and scientists to identify potential instrument problems. Developers continued to support USCRN scientists in the monthly assessment through on-the-fly production of soil measurement plots including plotting sensors individually, and producing 3-panel graphs with statistics on soil sensor values (dielectric constants, precipitation, and volumetric soil moisture). In FY18, developers identified an efficiency opportunity, which once coded and implemented, resulted in significant time-savings for the manual inspection process. In addition, developers provided the USCRN team with a detailed analysis of monthly soil quality changes, as well as quantitative statistics on sensor status. Each month, some soil sensors improved, while approximately 10 to 30 are exhibiting erroneous soil moisture or temperature values either due to short-duration issues or long-term problems, possibly requiring repair or replacement. So that inaccurate data are not provided to the user community, the identified sensors are added to the “bad sensor list” each month. After sensor problems are resolved by ATDD engineers in the field, the sensors are removed from the list of bad sensors. These activities are accomplished through close collaboration with ATDD engineers.

Data and Analysis Support for Scientists/Engineers
Software developers fulfilled several data pull requests in support of internal and external USCRN scientific and engineering research inquiries, and provided analysis and research support on several occasions. This included support to scientists at the Institute for Earth Science Research and Education, Oklahoma University School of Meteorology, USDA/ARS, Centers for Disease Control and Prevention, and the Utah Climate Center.

The developers also provided assistance for a number of internal scientific activities, including SCAN in situ soil data and AMSR-E satellite soil moisture data. Developers began updating FTP products software to include an additional ‘internal’ soils product for use by USCRN scientists and engineers with completion expected in FY19. Additionally development began on a Standardized Soil Moisture Product that is intended to assist with drought monitoring.

In FY18, ATDD engineers completed the process of removing Hydra soil sensors in one (or two) of three holes (at all depths) and replacing them with Acclima probes for testing at 10 pre-selected stations. Following each installation, the software developers manually flagged the Acclima test data to ensure its values are not used in the official layer averages for soil moisture and temperature. Additionally, they updated plotting code to display the test sensors and provided data, plots, statistics, and analysis comparing the soil moisture and soil temperature behavior of the two sensor types. Developers designed and updated a spreadsheet system to easily assess and compare sensor behavior at the test sites from month to month. Results were presented monthly to the USCRN team and at the All-Hands Team Meeting in Oak Ridge, TN (Nov 2018). This analysis is incorporated into the NOAA Technical Memorandum that examines the possible transition from Hydra to Acclima soil sensors.

Archive Submission Implementation
Developers transmitted and verified the successful archive of all USCRN data (experimental, FTP products, netCDF files, raw files transmitted over NOAAPort and satellite transmission) by NCEI’s

Archive Branch on a monthly basis. Scripts were written to automate the monthly processing (package/send files to Archive Branch) and to verify that all legacy data had been archived properly. In addition, the developers wrote scripts to ensure that all datalogger (i.e. PDA files) data (archived by NCEI Archive Branch directly) were properly archived. The new datalogger verification script began to be used on a routine basis and has already on at least four occasions revealed that some files for FY18 were not properly archived. All issues were resolved in cooperation with the Archive Branch.

ISD Processing

Developers planned and executed the successful migration of USCRN's Integrated Surface Data (ISD) dataset software to a new modern platform. The ISD dataset, which contains sub-daily, daily and monthly data from stations around the world, is NCEI's most used source of climate information and is the source of data that is accessible via online Local Climatological Data (LCD) reports. This work necessitated a software rewrite due to the hard-coded and brittle nature of the legacy CRN-to-ISD software package, which others developed in the earliest years of the USCRN program. During the rewrite, cross-division conversations held with the recipients of USCRN's ISD data files identified that it would be more efficient to maintain larger files that contained annual data sets. In order to verify the accuracy of the new software, scripts were written to facilitate the comparison of thousands of difficult-to-interpret sub-hourly, hourly, daily and monthly records. After validation, deployment and configuration of the rewritten software to the USCRN production server made it possible to keep all ISD files up-to-date with once-a-day delivery of USCRN data to downstream users at NCEI.

DOMSAT to HRIT Transition

USCRN has traditionally used the Domestic Satellite (DOMSAT) system as a backup data source for the GOES DCS data stream. Early in 2018 USCRN was notified that DOMSAT was scheduled to be discontinued on May 14th, 2019. Plans were made to replace the existing DOMSAT satellite dish, receiver and converter appliance at NCEI with an LRIT/HRIT compatible system. The HRIT (High Rate Information Transmission) broadcast is provided from the GOES satellites and carries the DCS data stream among many other data types. Developers provided technical support for the acquisition and transition to the new HRIT system. An analysis by the USCRN data manager identified the Microcom DAMS-NT DigiRIT system to replace the DOMSAT equipment. This included the necessary satellite dish and appliance for receiving, decoding, and distributing the HRIT data stream. It is a self-contained system with custom hardware for acquiring the satellite signal and decoding the serial data. Once obtained, the data are made available through an Ethernet port that can be connected to the OpenDCS server software already running on USCRN's production virtual machine (crn-prod). Plans include installation and training of the developers in early FY19.

Station Name Change

Developers helped facilitate the station name change for Utqiagvik, AK (formerly Barrow). This included alterations to the USCRN website and product documentation. Detailed discussions and analysis with program partners took place before the change took place.

Rolling-12 Validation

The rolling-12 is a set of temperature and precipitation data points appended to the end of each transmission for most USCRN stations. These are not official values, rather they provide near-real time information to support NWS forecast and warning activities through the NWS

Hydrometeorological Automated Data System (HADS). To verify the accuracy of the rolling-12 observations, developers acquired precipitation data from HADS for comparison against the official USCRN observations. In the early phase of work developers identified brief periods of time when the rolling-12 was misinterpreted for some stations, presenting temperature as precipitation by mistake. Upon notification of the problem, NWS personnel with the HADS program quickly made a correction before the USCRN analysis began. The analysis led to results that were as expected, with precipitation reported with sufficient accuracy for support of NWS forecasts and warnings.

Website Changes
Updates to the USCRN website included addition of significant USCRN events and annual reports as needed. Additionally old visualizations were retired and security issues addressed as newly identified issues arose. Occasionally the website would become unresponsive, along with several other websites unrelated to USCRN which are all hosted on the same Tomcat web server. Due to these interruptions, NCEI's IT division and the USCRN developers began discussions to develop a new web server cluster that will avoid such problems in the future through hosting of each website on an independent server. This reorganization is intended to improve uptime by preventing impacts to USCRN when another website suffers a failure. In addition, this will simplify logging and deployment for each website.

CS2 Transmitter Migration
An upgrade of the USCRN satellite transmitters from CS1 to CS2 began in FY18. The CS2 transmitters use one-half the bandwidth of the legacy transmitters, supporting the broader US goal of increasing transmission capacity for government and commercial satellite communication. The start of this upgrade carried several consequences for back-end USCRN data processing. The primary concern was that more than one GOES platform identifier would be associated with a station. Developers did not envision such a situation at the time of original design of the software and database, so it became necessary to expand the capabilities of these components. First, the Integrated Station Information System (ISIS), which is used by the USCRN as a repository for station metadata, was extended to represent events where a station's GOES platform identifier changed. Second, scripts were developed to routinely update the list of platform identifiers that were accepted by the USCRN's LRGS server; so that changes to ISIS would automatically add or remove GOES platform identifiers in that list. Lastly, updates to the USCRN database and Ingest software were made to map a GOES platform identifier to the correct station based on the timestamp of a received transmission. Once completed, ATDD engineers were able to install the new transmitters and assign new platform identifiers without issue. During these upgrades personnel from USCRN and ATDD coordinated closely to ensure that all transmitted observations were received and ingested.

USCRN Science and Development Activities
USCRN Climate Science Team made substantial process in its primary goal of improving the utility of soil moisture observations through standardization. The base standardized soil moisture dataset has been revised and published, and has begun the NCEI approval process. In the meantime work is progressing on using the standardized soil moisture data to better characterize drought in the U.S. through developing innovative indices. The expansion of the standardization work to other soil moisture sources such as satellite remotely sensed estimates is also underway.

In addition to the primary effort on soil moisture, a project examining the scientific basis of USCRN siting criteria was completed and published. A prototype National Precipitation Index has been developed that will eventually be deployed with the existing National Temperature Index on the NOAA NCEI Climate at a Glance page. Team members have collaborated with a number of colleagues on using USCRN precipitation and infrared surface temperature for satellite product validation, and temperature/humidity data for heat/health product development. Finally, the Climate Science Team continues to monitor the health of the USCRN and quality control observations, and assist with issues as requested.

1) Standardized Soil Moisture and Drought Indices

Leeper, R. D., J. E. Bell, and M. A. Palecki, 2019. A Description and Evaluation of U.S. Climate Reference Network Standardized Soil Moisture Dataset. *Journal of Applied Meteorology and Climatology.* DOI: 10.1175/JAMC-D-18-0269.1. (Submitted in 2018).

Poster (Leeper). An Evaluation of Recent U.S. Drought Events Using a Newly Available Standardized Soil Moisture Dataset, at the 98th American Meteorological Society Annual Meeting, Austin, TX, January, 2018.

Presentation (Leeper). Standardizing USCRN Soil Moisture Observations for Near-Real time applications, at the MOISST Conference, June 2018.

Poster (Palecki). Using Standardized Soil Moisture Indices for Drought Monitoring, at the MOISST Conference, June 2018.

Invited Presentation (Leeper). Standardizing Short-Term Soil Moisture Datasets, at The 5th Satellite Soil Moisture Validation and Application Workshop, Fairfax, VA, October 2018.

Poster (Leeper). Standardizing Short-Term Satellite Soil Moisture Datasets, at the SMAP Cal/Val Workshop #9, Fairfax, VA, October 2018.

Poster (Palecki). Using Standardized Soil Moisture Indices for Drought Monitoring, at the American Geophysical Union Fall Meeting, Washington, D.C. December 2018.

The interpretation of in situ or remotely sensed soil moisture data for drought monitoring is challenged by the sensitivity of these observations to local soil characteristics and seasonal precipitation patterns. These challenges can be overcome by standardizing soil moisture observations. Traditional approaches require a lengthy record (usually 30 years) that most soil monitoring networks lack. Sampling techniques that combine hourly measurements over a temporal window have been used in the literature to generate historical references (i.e., climatology) from shorter term datasets. This sampling approach was validated on select USDA Soil Climate Analysis Network (SCAN) stations using a Monte Carlo analysis, which revealed that shorter term (5+ years) hourly climatologies were similar to longer term (10+ year) hourly means. The sampling approach was then applied to soil moisture observations from the U.S. Climate Reference Network (USCRN). The sampling method was used to generate multiple measures of soil moisture (mean and median anomalies, standardized median anomaly by inter-quantile range, and volumetric) that were converted to percentiles using empirical cumulative distribution functions. Overall, time series of soil moisture percentile were very similar among the differing measures; however, there were times of year at individual stations where soil moisture percentiles could have substantial deviations

(Figure A). The use of soil moisture percentiles and counts of threshold exceedance provided more consistent measures of hydrological conditions than observed soil moisture (Figure B). These results suggest that hourly soil moisture observations can be reasonably standardized, and provide consistent measures of hydrological conditions across spatial and temporal scales.

Further work has commenced on the extension of these standardization concepts to unifying soil moisture estimates from in situ, satellite, and model sources (Figure C). Preliminary findings indicate that the relationship of soil moisture to drought status is complex, but percentile standardization does produce results that share some traits with existing drought indices (Figure D) while reacting more quickly and providing some nuance to tracking drought status evolution.

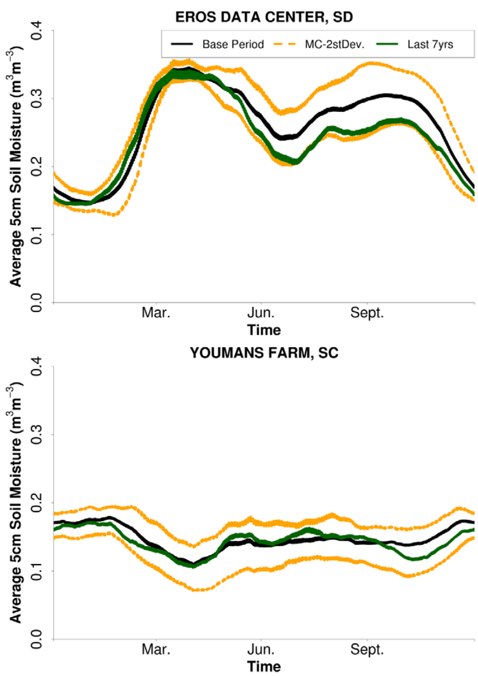


Figure A. Long term (black line) and last 7-year (green line) climatologies within two standard deviations of the 1000 randomized 7-year draws of the Monte Carlo simulation (orange dashed line) for the Eros Data Center, SD (top) and Youmans Farm, SC (bottom).

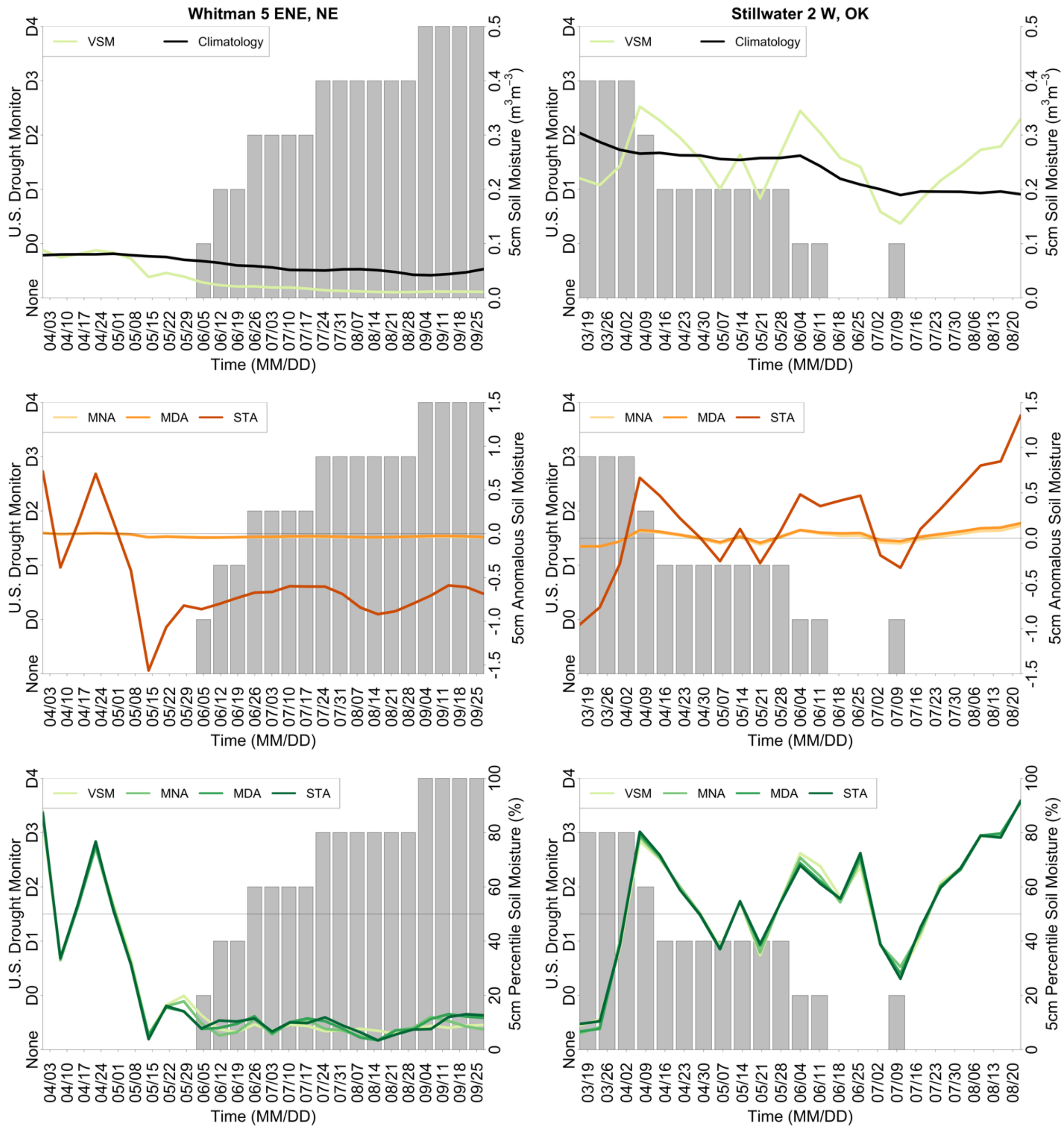


Figure B. 5 cm 7-day averaged volumetric (top), mean (MNA), median (MDA), and standardized median (STA) anomalies (middle), and volumetric (VSM), mean (MNA), median (MDA), and standardized median (STA) percentiles (bottom) soil moisture conditions at (left) Whitman, NE, during the rapid onset of drought conditions (gray bars) during the 2012 drought, and (right) Stillwater, OK during drought improvement in 2013. Standardized median anomalies (STA) were normalized by factor of ten (middle) to compare with mean and median based anomalies.

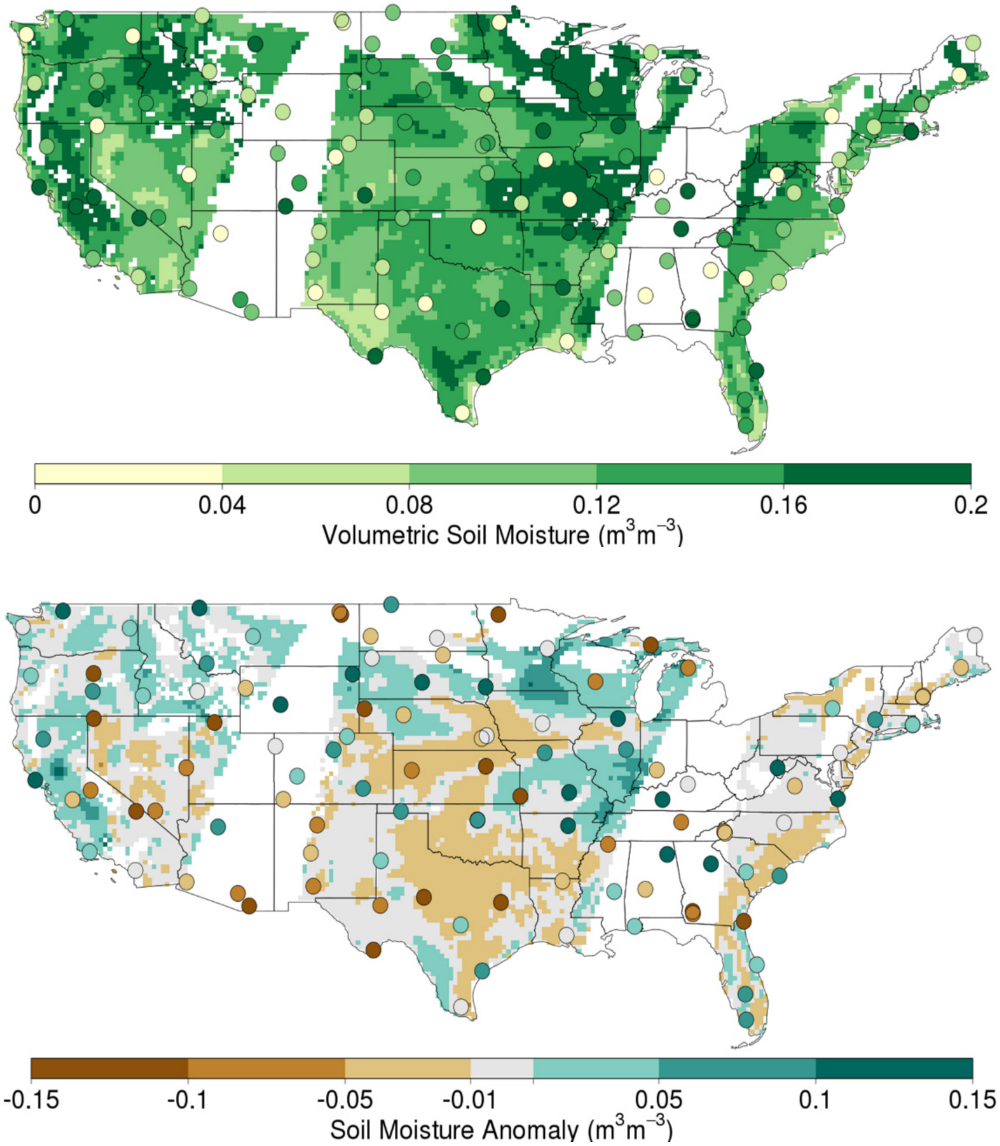


Figure C. AMSR-E and USCRN (2am) descending volumetric (top) and anomalous (bottom) soil moisture conditions for March, 21st 2011.

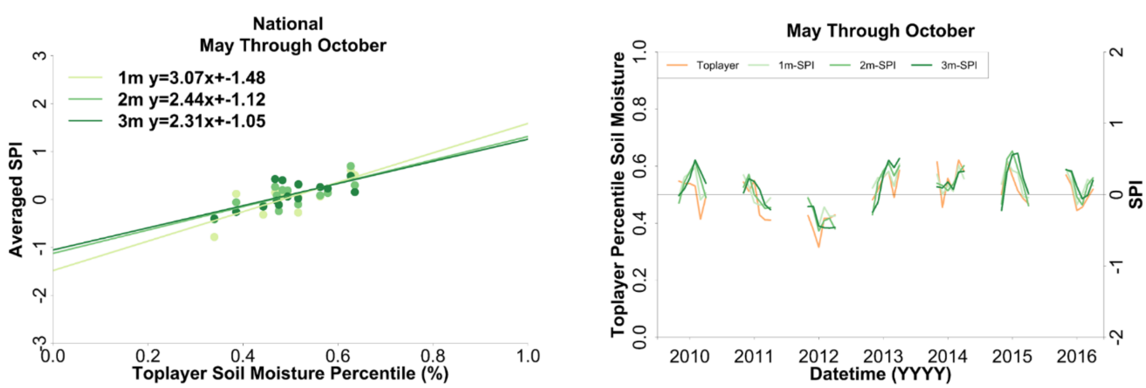


Figure D.

Comparing 1, 2, and 3 month standardized precipitation index values to the topsoil (5 and 10 cm) soil moisture percentiles of the USCRN averaged over the conterminous U.S. The regressions are significant at $p > 0.95$.

2) USCRN Siting Experiment

Leeper, D. R., J. Kochendorfer, T. Henderson, M. A. Palecki, 2019. Impacts of Small-Scale Urban Encroachment on Air Temperature Observations. *Journal of Applied Meteorology and Climatology.* DOI: 10.1175/JAMC-D-19-0002.1. (Submitted in 2018).

Poster (Leeper). The Sensitivity of Temperature Measurements to Built-Up Environments: A Case Study in Oak Ridge, TN, at the 99th American Meteorological Society Annual Meeting, Phoenix, AZ, January 2019.

A field experiment was performed in Oak Ridge, TN, with four instrumented towers placed over grass at increasing distances (4, 30/50, 124, and 300 m) from a built-up area. Stations were aligned in such a way to simulate the impact of small-scale encroachment on temperature observations. Temperature observations were warmest for the site closest to the built environment with an average temperature difference of 0.31 and 0.24 ºC for aspirated and unaspirated sensors respectively. Mean aspirated temperature differences were greater during the evening (0.47 ºC) than day (0.16 ºC). Evenings following greater daytime solar insolation and wind from the built area showed the largest effect (Figure E). The impact of the built environment on air temperature diminished with distance and was not detected at 124 m.

The experimental findings were comparable to a known case of encroachment at a U. S. Climate Reference Network station in Kingston, RI (Figure F). The experimental and operational results both lead to reductions in the diurnal temperature range of ~0.39 ºC for fan aspirated sensors. Interestingly, the unaspirated sensor had a larger reduction in DTR of 0.48 ºC. These results suggest that small-scale urban encroachment within 50 meters of a station can have important impacts on daily temperature extrema (maximum and minimum) with the magnitude of these differences dependent upon prevailing environmental conditions and sensing technology.

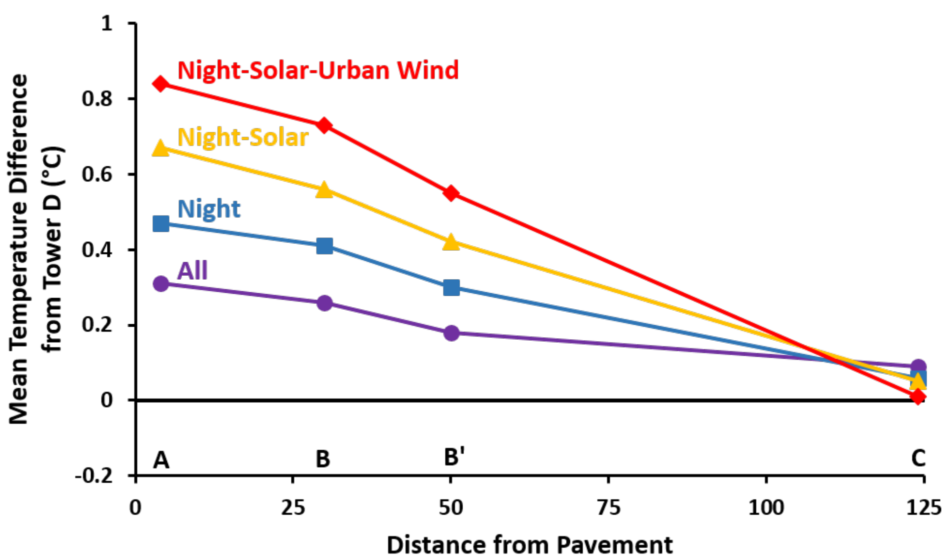


Figure E. Mean aspirated temperature differences with respect to tower D for all conditions (black line), nocturnal observations (blue), nocturnal observations on days receiving more than 20 MJ solar radiation (yellow), and nocturnal observations on high solar receipt days with wind from the urban area compass directions 225-315° (red).

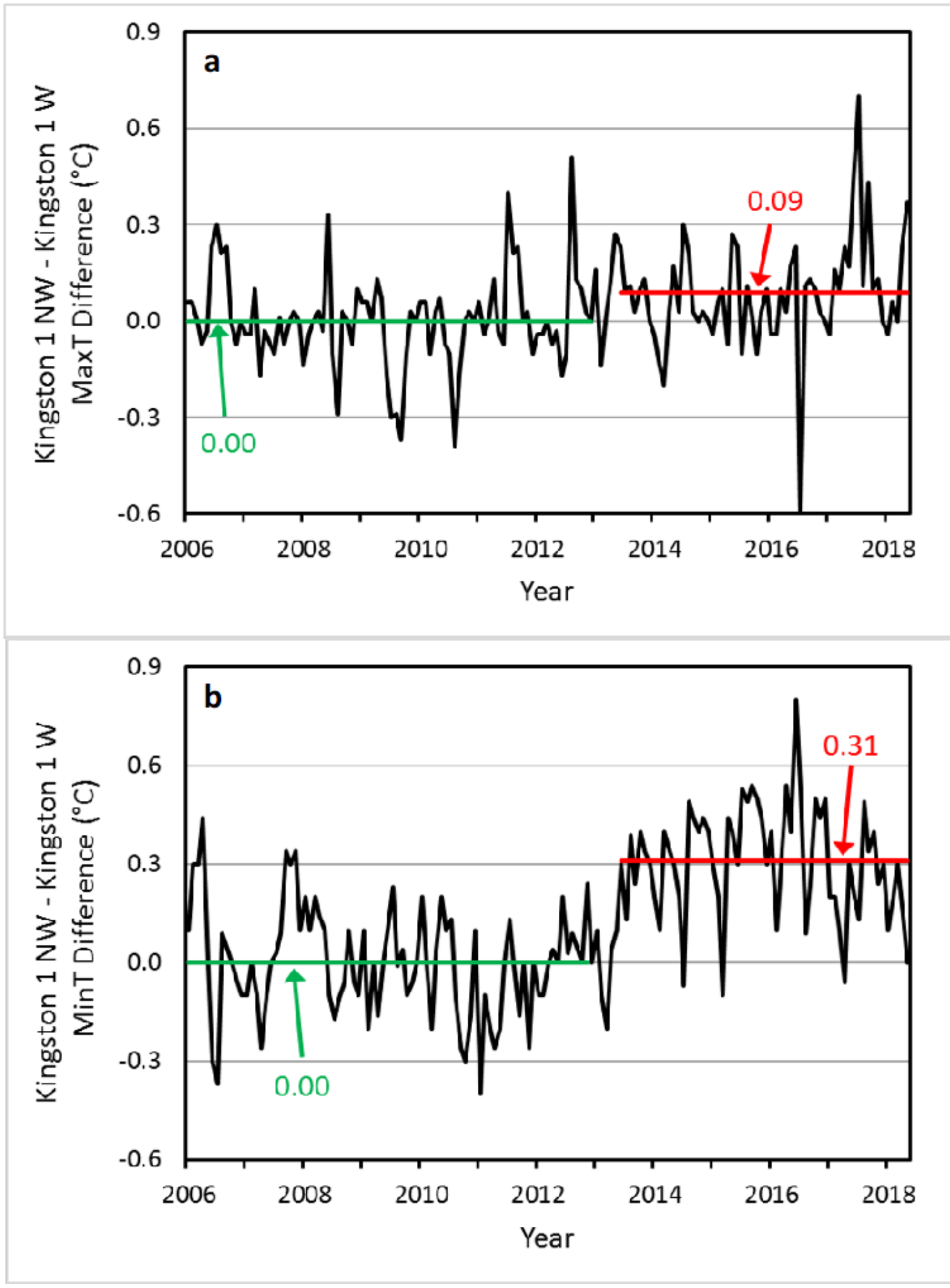


Figure F. The monthly mean air temperature difference anomalies between Kingston 1 NW and Kingston 1 W USCRN stations: a) daily maximum temperature (MaxT); b) daily minimum temperature (MinT). The green lines indicate the average monthly differences from January 2006 through December 2012; the red lines indicate the average monthly differences from June 2013 through May 2018 after the built environment was installed in 2013.

3) National Precipitation Index Development

Rennie, J., and M. A. Palecki. United States Climate Reference Network National Precipitation Index. White Paper (In preparation)

NOAA's National Centers for Environmental Information (NCEI) produces a monthly National Temperature Index (NTI), a set of calculations of air temperature for the contiguous United States at the monthly, seasonal and annual time scales. Two versions of NTI are displayed, one of which is derived using only the stations from the United States Climate Reference Network (USCRN), and the other a compilation of thousands of stations across the U.S. interpolated onto a 5 kilometer resolution gridded temperature product called nClimGrid. USCRN was developed to provide long-term homogeneous observations for the detection and attribution of present and future climate change, and is used as a reference to see how well the historical stations measure U.S. climate. The current work is expanding this concept to continental-scale precipitation totals using an analogous approach, comparing NCEI's Climate at a Glance (CAG) national monthly, seasonal, and annual precipitation departures from normal based on the previously mentioned 5 kilometer gridded data set with an index derived from USCRN precipitation observations.

Estimated normal precipitation for each USCRN station is based on the normals for the four grid points closest to the station location, adjusted using a regression between the USCRN station observations and the gridded observations between 2006 and 2018. These station departures were then combined in three ways to derive a national index: simple average of all the stations, coarse grid averaging with no interpolation, and fine grid averaging with interpolation. The quality of the placement and distribution of the 114 USCRN stations resulted in the simple station average giving the best relationship, explaining 92% of the variance on an annual basis and 87% of the variance at a monthly basis (Figure G).

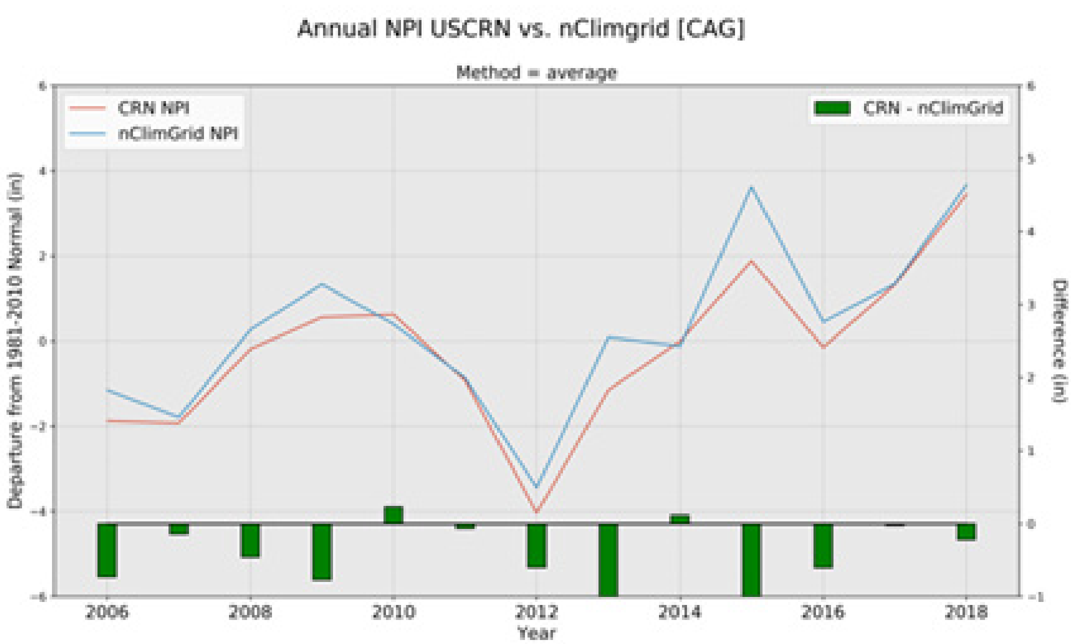


Figure G. USCRN NPI (red) and CAG NPI (blue) display a high degree of agreement on an annual basis.

4) USCRN Observation Applications and Collaborative Research

a) Using Ancillary Information from Radar-based Observations and Rain Gauges to Identify Error and Bias. Nelson, B., O. Prat, and D. R. Leeper. (Research collaboration in progress)

Presentation (Leeper). Use of NEXRAD Radar-Based Observations for Quality Control of In Situ Rain Gauge Measurements, at the American Geophysical Union, New Orleans, LA, December 2017.

Ancillary information regarding precipitation type, air temperature, and radar quality provide an opportunity to better quantify and enhance radar based measures of precipitation. In this study, radar-based precipitation estimates from NOAA's NEXRAD Reanalysis (NNR) and National Centers for Environmental Prediction (NCEP) stage IV products were compared to aggregates of USCRN's 5-minute precipitation by temperature, precipitation type, and radar quality. Interestingly, the requirement of USCRN for 5-minute precipitation totals to exceed 0.2 mm to be recorded seems to degrade the timing of the precipitation enough to cause substantial bias in the 5-minute results as compared to the hourly results (Figure H).

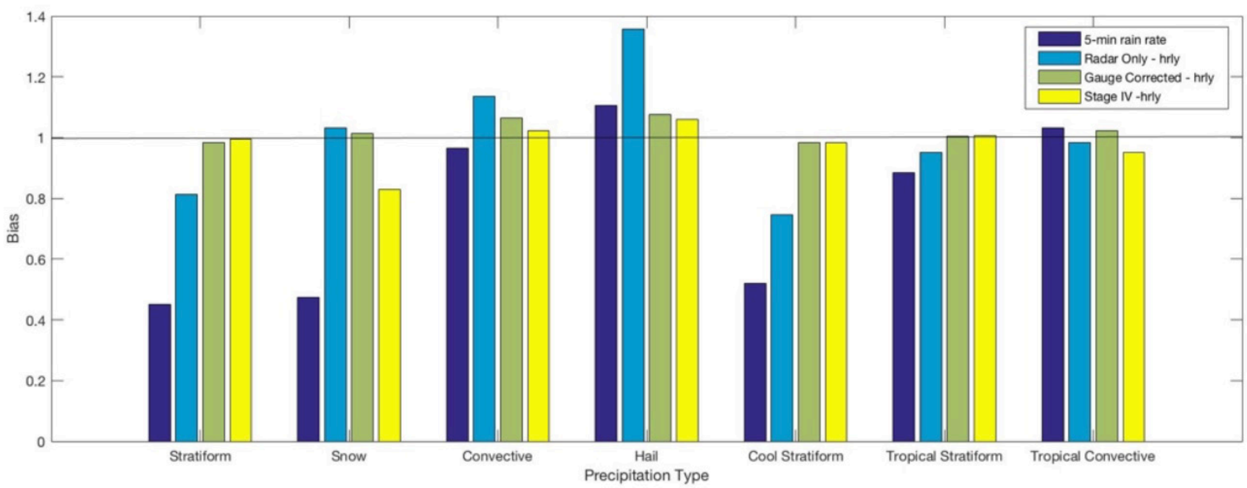


Figure H. Bias for each type of precipitation for the four different rain gauge – radar comparisons (5-minute gauge – precipitation rate; hourly gauge – radar only; hourly gauge – gauge corrected radar; hourly gauge – stage IV).

b) Reconstruction of Hourly Land Surface Temperature from Time Series of Daily Max/Min Temperatures Iramdar, A., and D. R. Leeper. *Journal of Geophysical Research* (In Preparation)

Poster (Leeper). On the Inter-relationship between Land Surface Air Temperature and Skin Temperature, at the 99th American Meteorological Society Annual Meeting, Phoenix, AZ, January 2019.

Polar orbit satellite based measures of land surface temperature are at best limited to four measurements per day, which may be further constrained by the presence of clouds during satellite overpasses. In this study, a novel approach was explored to estimate hourly land surface temperatures for all sky conditions using daily measures of maximum and minimum temperatures from the Global Historical Climatology Network (GHCN). Hourly estimated LST were compared against USCRN and SURFRAD LST observations, with reasonable results even on cloudy days (Figure H).

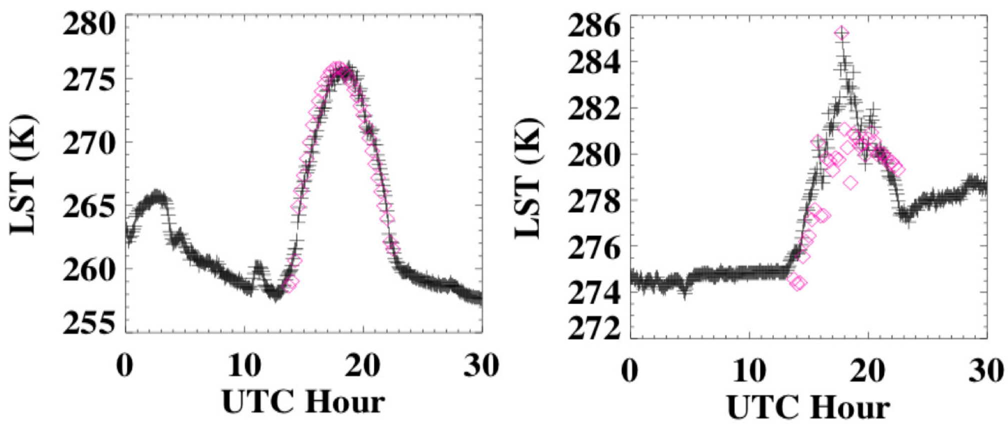


Figure H. USCRN (black) and modeled (purple) hourly land surface temperatures at Bowling Green, KY for clear (left) and cloudy (right) days.

c) Quality Control and Processing of Cooperative Observer Network Hourly Precipitation Data Lawrimore, H. J., D. Wuertz, S. Stevens, M. A. Palecki, D. R. Leeper, **B.** Krozeniewski, K. Lowrie, and T. Trunk. *Journal of Hydrometeorology* (In preparation)

Presentation (Lawrimore). Improved Hourly and Sub-Hourly Gauge Data for Assessing Precipitation Extremes in the U.S., at the American Geophysical Union, New Orleans, LA, December, 2017.

A new quality control algorithm has been developed for the Cooperative Observer Program's (COOP) digital hourly precipitation dataset (HPD). This study evaluated the new quality control process to ensure the continuity of the data record between the network's legacy and digital eras as well as its performance against the Global Historical Climatology Network (GHCN) and the U.S. Climate Reference Network (USCRN) datasets. The HPD relationship to USCRN was examined for large precipitation events (Figure I) and for presumptive zero precipitation periods. The relationships were strong for both situations, although the HPD system tended to develop more noise and false precipitation findings in the middle of the day when under solar heating.

Figure I. Scatter plot showing the relationship between precipitation event totals (25.4mm or more) for GHCN and HPD (blue) and GHCN and USCRN (red).

d) Global evaluation of satellite based Quantitative Precipitation Estimates (QPEs) from the Reference Environmental Data Records (REDRs). O. P. Prat, B. R. Nelson, E. Nick, and R. D. Leeper. (Research collaboration in progress)

Presentation (Prat). Evaluation of Daily Extreme Precipitation Derived from Long-term Global Satellite Quantitative Precipitation Estimates (QPES) at the American Geophysical Union, New Orleans, LA, December 2017.

Evaluations of satellite precipitation estimates can be limited by mismatches between in-situ observation times and satellite overpasses. This is particularly pronounced for extreme precipitation events. In this study, U.S. Climate Reference Network precipitation data were used to evaluate a suite of satellite based (Persiann, CMORPH, & GPCP) estimates of precipitation. Comparisons with USCRN precipitation values on the day of the satellite produced quantitative precipitation estimates demonstrated that the CMORPH product created by the Climate Prediction Center from microwave imaging data matched very well at all value ranges above the USCRN minimum of 0.2 mm.

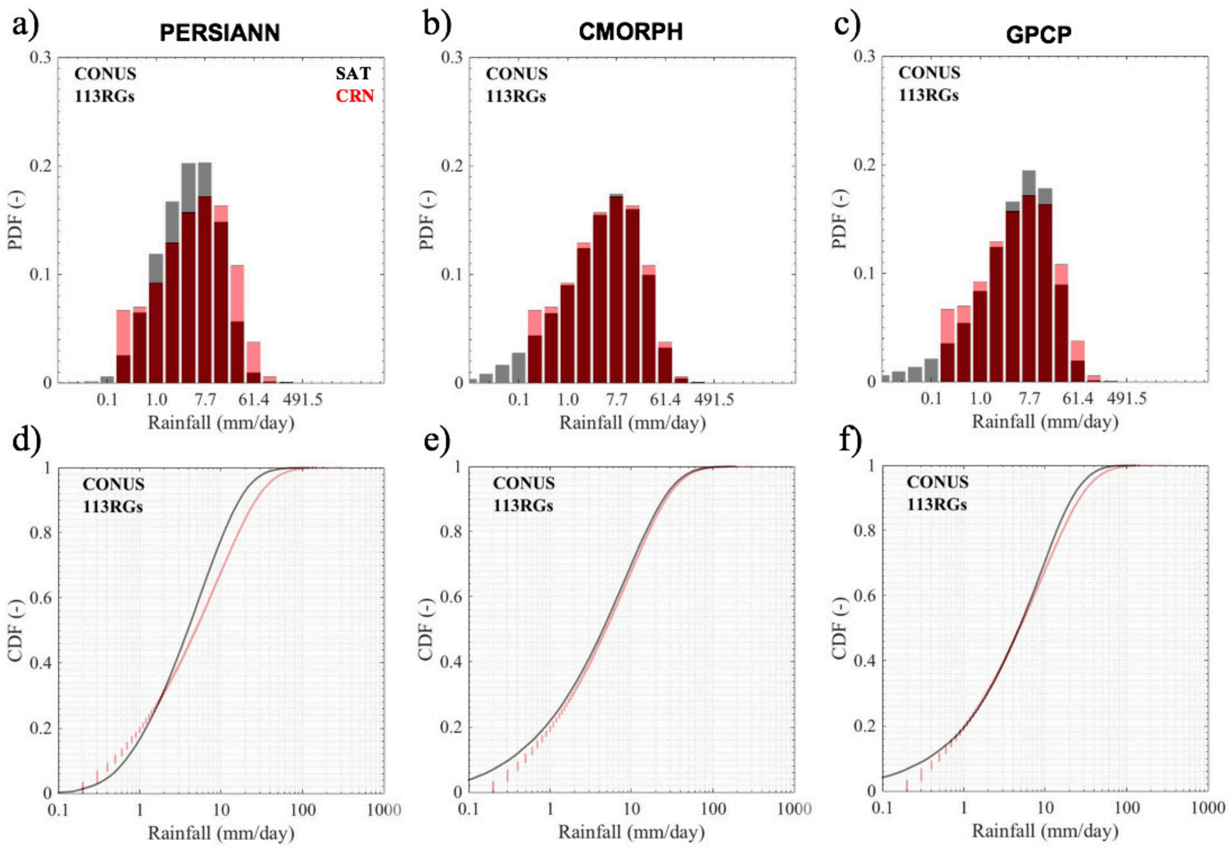


Figure J. (a-c) Distribution of daily rainfall for events observed simultaneously by USCRN stations and satellites; (a) PERSIANN-CDR, (b) CMORPH, and (c) GPCP. (d-e) Same but for the cumulative distribution function for USCRN stations and (d) PERSIANN-CDR, (e) CMORPH, and (f) GPCP for the period 2007-2015.

e) Application of USCRN Observations to Heat/Health Issues. M. A. Palecki, J. Rennie, and J. Bell. (Research collaboration in progress).

Presentation (Palecki). Utility of High Temporal Resolution Observations for Heat Health Event Characterization. American Geophysical Union Fall Meeting, New Orleans, LA, December 2017.

Project focuses on using the comprehensive collection of USCRN observations at 5-minute temporal resolution to better characterize heat events that can impact human health. Temperature, heat index, apparent temperature, and wet-bulb globe temperature are some of the measure of conditions being examined, along with differing methods of accumulating the effects. Preliminary examination of daily accumulation of minutes above given thresholds indicates a more information-rich approach to heat wave characterization. For example, during the late June-early July 2017 heat wave at Tucson, AZ, one can accumulate the number of minutes above certain extreme thresholds that needs to be endured by humans outdoors, or by air conditioning system, or by companies supplying electricity to the region.

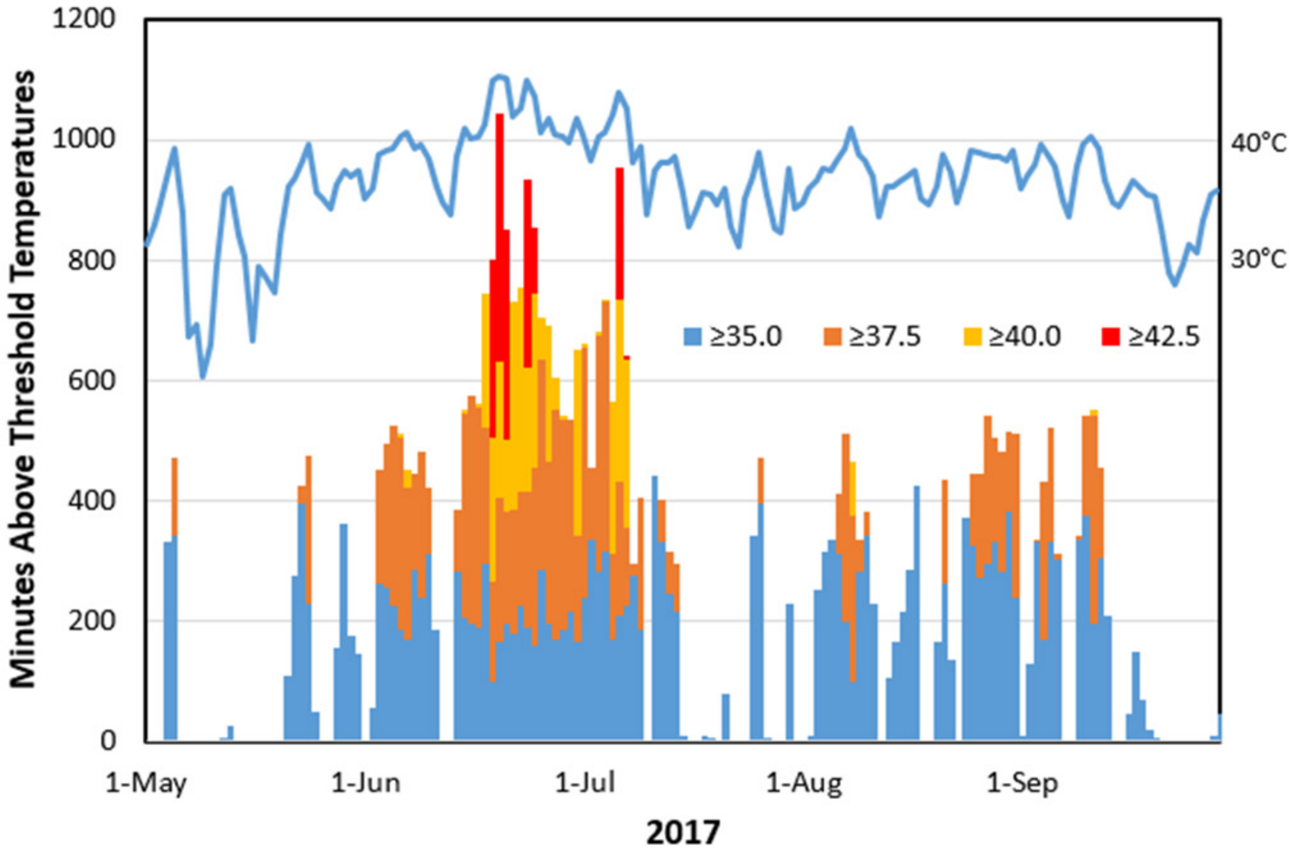


Figure K. Representation of the daily heat duration above the color-coded air temperature thresholds during the June-July 2017 heat wave at the Tucson, AZ USCRN station. The blue line is the daily maximum air temperature.

USCRN Marshall Testbed

In addition to routine maintenance of all of the sensors at the USCRN testbed at Marshall CO, much of FY18 was dedicated to the completion of the WMO Solid Precipitation Intercomparison Experiment (SPICE) final report, and the preparation of other publications. In addition, a new Low Porosity Double Fence (LPDF) precipitation wind shield was designed and built by USCRN personnel in Oak Ridge, TN, and in the fall of 2018 it was installed at the Marshall Testbed for evaluation beginning during the winter of 2018-2019.

The WMO-SPICE final report was completed in FY18, and published in early FY19 (Nitu et al., 2018). In addition, measurements from the USCRN testbed were used in one publication that was published in FY19 (Kochendorfer et al., 2018). It was determined that the same transfer function could be used on different types of weighing precipitation gauges, because wind shielding (or a lack thereof) was the primary determinant of the appropriate transfer function, as opposed to gauge type. In addition, uncertainty in the transfer function was found to be relatively constant with wind speed. However, due to the increasing magnitude of the transfer function adjustment with increasing wind and the multiplicative nature of the adjustment, errors in the adjusted measurements increased as the wind speed increased. Much work also went into deriving transfer functions for tipping bucket precipitation gauges. Multiple talks on this topic were given in FY18, and progress towards a publishable manuscript was made.

References

Nitu, R., Roulet, Y.-A., Wolff, M., Earle, M., Reverdin, A., Smith, C., Kochendorfer, J., Morin, S., Rasmussen, R., Wong, K., Alastrué, J., Arnold, L., Baker, B., Buisán, S., Collado, J.L., Colli, M., Collins, B., Gaydos, A., Hannula, H.-R., Hoover, J., Joe, P., Kontu, A., Laine, T., Lanza, L., Lanzinger, E., Lee, GW, Lejeune, Y., Leppänen, L., Mekis, E., Panel, J.-M., Poikonen, A., Ryu, S., Sabatini, F., Theriault, J., Yang, D., Genthon, C., van den Heuvel, F., Hirasawa, N., Konishi, H., Motoyoshi, H., Nakai, S., Nishimura, K., Senese, A., and Yamashita, K., (2018), WMO Solid Precipitation Intercomparison Experiment (SPICE) (2012 - 2015), WMO, IOM No. 131.

Kochendorfer, J., Nitu, R., Wolff, M., Mekis, E., Rasmussen, R., Baker, B., Earle, M. E., Reverdin, A., Wong, K., Smith, C. D., Yang, D., Roulet, Y.-A., Meyers, T., Buisan, S., Isaksen, K., Brækkan, R., Landolt, S., and Jachcik, A. (2018). Testing and development of transfer functions for weighing precipitation gauges in WMO-SPICE, Hydrol. Earth Syst. Sci., 22, 1437-1452, https://doi.org/10.5194/hess-22-1437-2018, 2018.

A Continuing Evaluation of New Soil Moisture/Temperature Sensor Technology

In 2009, Hydra Probes were deployed to automatically measure soil moisture across the 113 USCRN stations[2] in the conterminous US. The Hydra Probes, which conduct point measurements of soil water content, soil temperature, and bulk soil electrical conductivity, offer the ability to make automatic and continuous measurements under a wide range of soil type, water and temperature conditions. The principle behind the Hydra Probe is the very high dielectric constant of pure water (80) compare to that of mineral soils (4-16) and air (1) at 20 degree C. Hydra Probes compute the soil dielectric constant which is then converted to water content. The Hydra Probes generate a 50 MHz signal from which the dielectric is computed, although this calculation is subject to some errors for soils with high conductivities. Soil specific calibration equations are required to convert the dielectric constant to water content. For USCRN, since site-specific calibrations were not performed before deploying the Hydra Probes, soil water content measurements are based on calibration equations developed for loamy soil types by Seyfried et al. (Vadose Zone Journal 4:1070–1079 (2005), doi:10.2136/vzj2004.0148).

Despite the general success of the USCRN soil moisture measurements, investigations of the Hydra Probe performance over several years have revealed the need for further evaluation. Hydra Probes have performed poorly in soils with relatively high clay content. This poor performance is attributed to both the clay content and the clay mineralogy interaction with water content and temperature. Hydra Probe dielectric constant measurements are strongly influenced by clay properties such as surface area and CEC. This is an issue that cannot be addressed by using factory-supplied calibration equations for clay, because they are generalized equations based on soil texture types, not on the mineralogy of a particular soil type. The Hydra Probe may be unsuitable for certain clay soils. An alternative for USCRN has been to replace the Hydra Probe with the Acclima Probe, which offers an affordable alternative by using time domain reflectometry (TDR), which is considered to be one of the best methods for measuring soil moisture.

[2] The USCRN network in the conterminous US has 114 stations, but one (Torrey, UT) has rocky soil precluding the installation of any soil sensors.

In light of this effort, since June 2016, the Hydra Probe and the Acclima Probe have been evaluated in a homogeneously packed coarse loamy soil testbed in the immediate vicinity of a USCRN test site in Oak Ridge, TN. The testbed covers a rectangular area about 130 cm x 245 cm and about 20 cm high above the natural ground. Uniform grass cover is maintained over both testbed and the surrounding ground. The average bulk density of the soil in the testbed is about 1.17 gm cm^{-3}. Four Hydra probes buried at 10 cm were used to measure volumetric soil water content and soil temperature. Both variables were also measured with four Acclima probes, also buried at 10 cm. The probes were about 25 cm apart. To validate the soil water measurement, gravimetric soil water measurements have been used, as well as soil water measurements from multiple Decagon sensors and an EnviroPro sensor.

As a result of this a new USCRN Technical Memorandum was begun in FY2018 by the scientific and technical staffs at OAR's Atmospheric Turbulence and Diffusion Division, in partnership with NESDIS' National Centers for Environmental Information. The Technical Memorandum will be the formal and well-researched documentation to justify the addition of a new sensor to the USCRN suite of instrumentation. This analysis has been conducted from the standpoint of long-term sustainability, cost, technical performance, performance in high clay soils, and comparative data from both probes which we will show will have essentially no impact on the long-term climate record. These areas are all well-documented in the body of this document, and therefore, the overall recommendation of this analysis will be to allow for an eventual transition from the Hydra to Acclima TDR-315L with no negative impacts on the long-term USCRN climate record and this will be well-documented in the body of this Technical Memorandum. On the contrary, we believe that this replacement probe will not only improve the overall climate record particular in its operation in clay soil stations, but will be far more affordable and sustainable in the future allowing for a continued and improved overall climate record. We expect this memo to be issued sometime in FY2019.

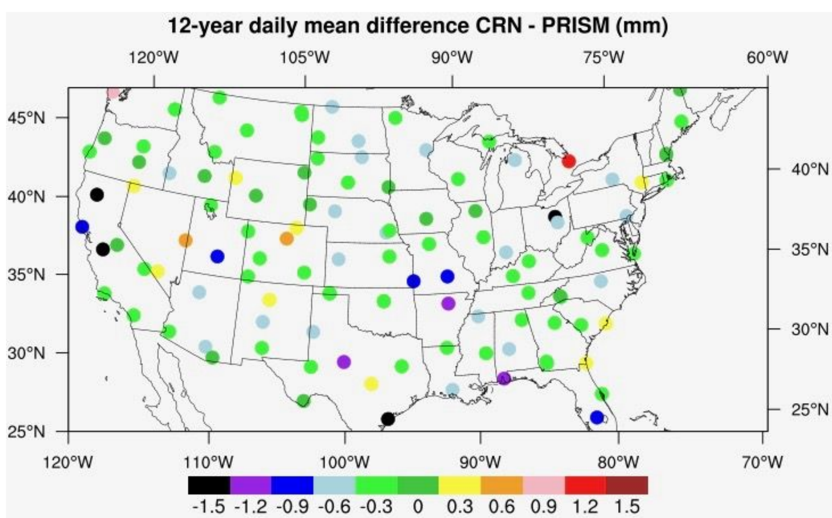
The Production of Gridded USCRN Data

To address a need for an enhanced utilization of the US Climate Reference Network (USCRN) dataset, a gridded product was produced. Daily means of more than 20 variables were computed, going back to at least 2006. In addition to the 114 conterminous USCRN stations analyzed, an additional 70 former Regional USCRN stations (RUSCRN) in the southwest US and Alabama (some of which are now run by the state climatologists in those states) were included to increase data coverage. These data were then analyzed to a grid and resulting analyses were output into a common netCDF format for use by the larger meteorological community. A brief description of this process follows.

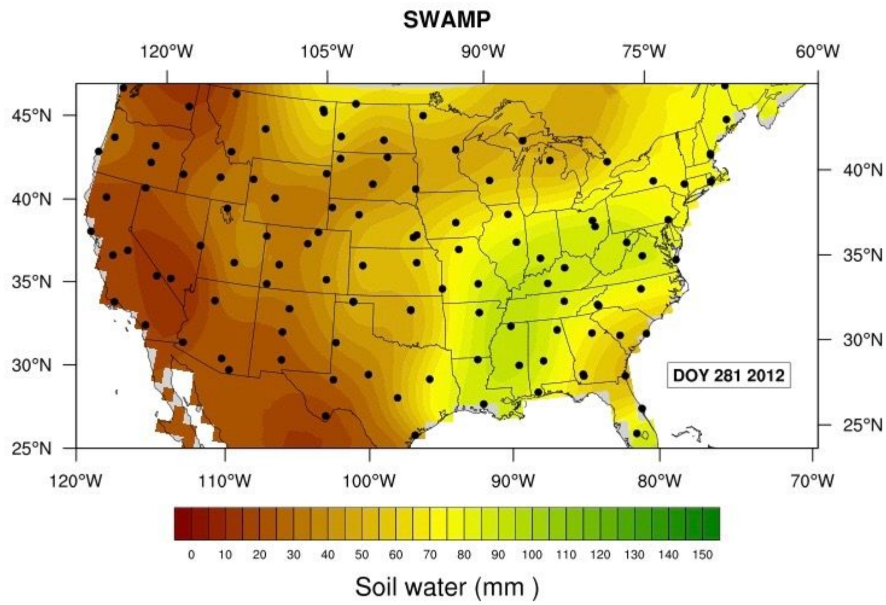
After daily means of variables (e.g., air temperature, relative humidity, soil moisture and temperature, etc.) were computed, the freely available National Center for Atmospheric Research (NCAR) NCAR Command Language (NCL) was used to objectively analyze the data on to a 0.2° by 0.2° grid spanning from 20°N to 50°N and from 125°W to 60°W, covering the continental US. This was accomplished using a two-pass Barnes Objective analysis scheme. In this process, a first pass is completed using a relatively large region of influence, where data within a 6.0° radius were included in the analyses. Then a second pass was used to improve the analysis using a 1.0° radius of influence and a small convergence parameter to reduce the spectral response.

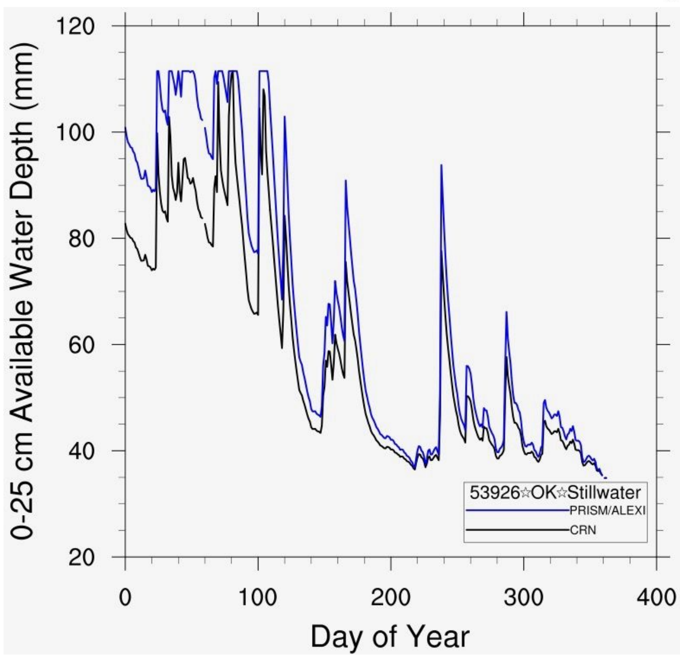
Once the analyses were produced, individual yearly animated .gifs were produced to visualize the data. These were output to netCDF files, with each file containing one variable for all days that the variable was available. For the files with the entire 11-year record, this corresponds to 4018 days. The files contain standard netCDF conventions as attributes, such as standard names, units, etc. They also contain "long names" for a more descriptive means for identifying the data included in each file. The time units are "days since 2006-01-01 00:00:00" as this was the first time period of the analyses. The analyses have been uploaded to the ATDD ftp server and can be found at ftp://ftp.atdd.noaa.gov/CI/crn/gridded/netCDF/archive/alldays/.

The soil water content measurement by the USCRN is an essential variable with the potential to improve agricultural water management, climate and weather predictions, hydrological modeling, and ecological studies. Large-scale numerical models and satellite observations are often used to provide routine products of gridded soil moisture nationwide across the United States. The objective of this study was to use in situ USCRN soil water content measurements to evaluate the performance of two gridded models: The Parameter-elevation Relationships on Independent Slopes Model (PRISM) and the Atmosphere-Land Exchange Inverse (ALEXI) model. The models were evaluated based on measurements from 114 USCRN stations that have been in operation since 2009. Predicted soil moisture was based on precipitation input obtained using the PRISM model and evapotranspiration from the ALEXI model, along with soil property data from the U.S. soil survey database (SSURGO/STATSGO). The model performed acceptably in predicting available soil water in the top soil depth of 25 cm. The predicted mean daily precipitation integrated over multiple years showed differences less than 1 mm. Discrepancies between predicted and measured precipitation were largest during the spring season in the south U.S. with wet conditions and in the southwestern



U.S. with dry conditions as soil contributions dominated the energy budget of the model prediction of evapotranspiration. Work to expand the use of USCRN soil moisture in gridded product development is continuing in earnest. Plans are underway to obtain detailed site-specific soil property information across all the USCRN stations to improve soil moisture measurements and fine tune gridded model predictions of soil moisture.





FY18 Accomplishments of USCRN Team on USCRN Soil Moisture and Drought Work

A great deal has been accomplished this year with regards to USCRN soil moisture and drought work. However, some activities slowed briefly during the transition of Jesse Bell to the University of Nebraska and the assumption of his duties by other USCRN Team members. This transition is now complete and planned activities are on track with a slight offset to completion time lines.

Activity 1: USCRN Soil Moisture Operations and Ongoing Improvements

- A system for producing graphics of all USCRN soil moisture and soil temperature time series for the previous month was improved.
- Manual soil moisture QC operations used the improved outputs to capture quality issues more efficiently and flag questionable values more reliably and notify ATDD of resulting issues.
- Additional data processing and visualization support was provided to ATDD for testing the Acclima soil moisture probe against the existing Hydra Probe technology currently used Figure 2).

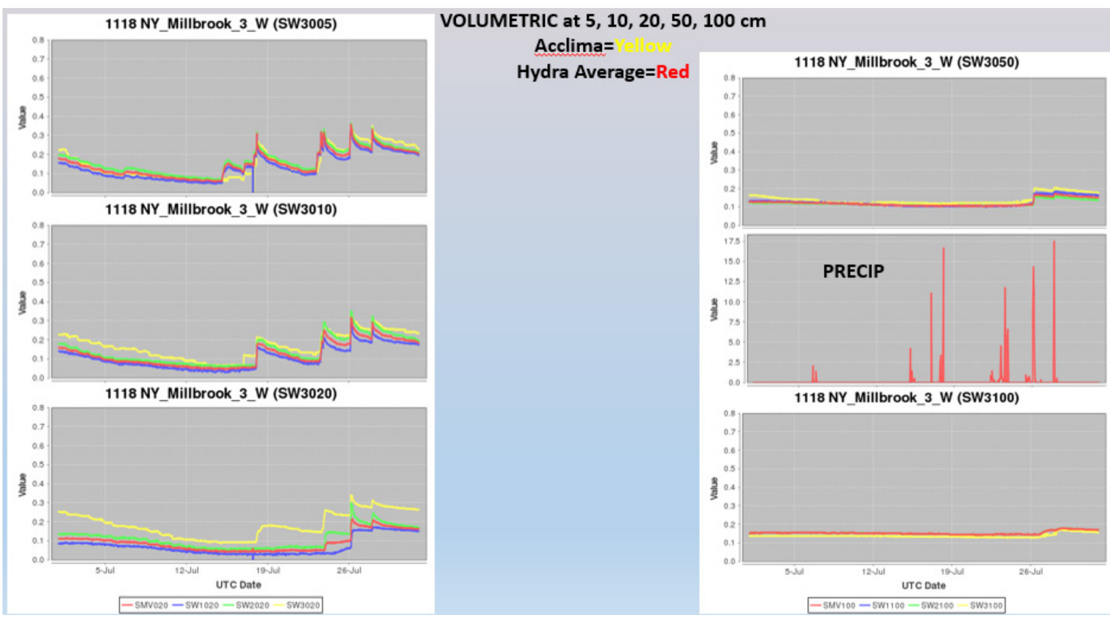


Figure 2. Comparison of Acclima probe soil moisture (yellow) and Hydra Probe average (red).

Activity 2: Standardized Soil Moisture Product (Beta release and journal article submission)

- Beta product development is completed, consisting of soil moisture climatology and standardized soil moisture data files for each USCRN station.
- Transition to operational status is progressing by moving the development software to the CRN production system and preparing for an Operational Readiness Review.
- A journal article was submitted for publication describing the standardized soil moisture product and the early work on the drought indices product (Fig. 2):

Leeper, R. D., J. E. Bell, and M. A. Palecki. A description and evaluation of U.S. Climate Reference Network standardized soil moisture dataset. Submitted to J. Applied Meteorology and Climatology.

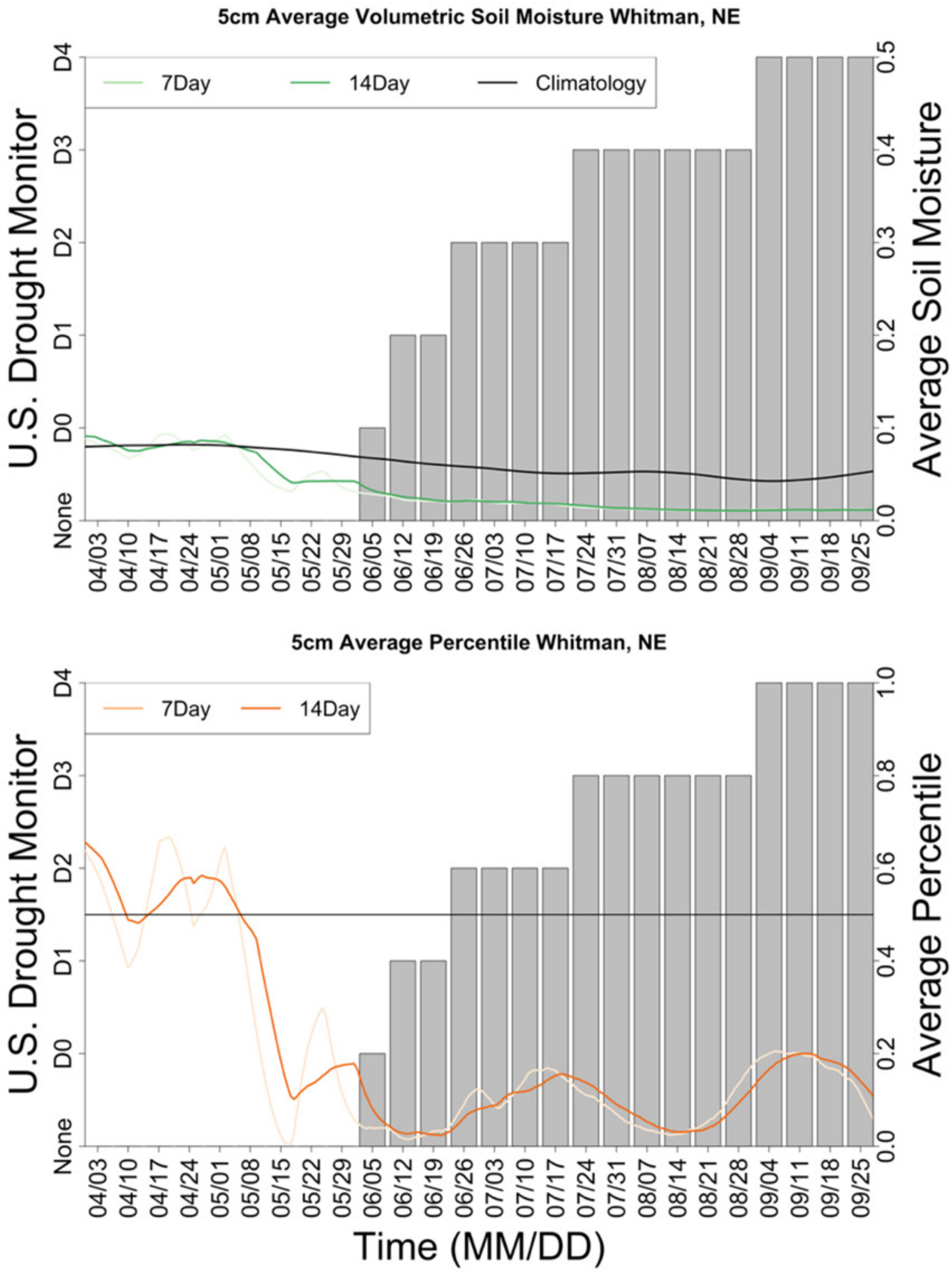


Figure 3. 7- and 14-day averaged volumetric (top) and percentile (bottom) 5 cm soil moisture conditions at Whitman, NE, during the rapid onset of drought conditions (gray bars) during the 2012 drought. Note the much larger response of the standardized soil moisture percentiles in the bottom graph.

Activity 3: Applications of Standardized Soil Moisture Product (Applied research to improve drought characterization leading to a journal article submission)

- The Leeper et al. journal article included an example application of the standardized soil moisture percentile product as a drought index derived by creating 7-day and 14-day average percentiles, as shown in Fig 2.
- Further work comparing average soil moisture percentiles to common drought indices has begun (Fig. 3).

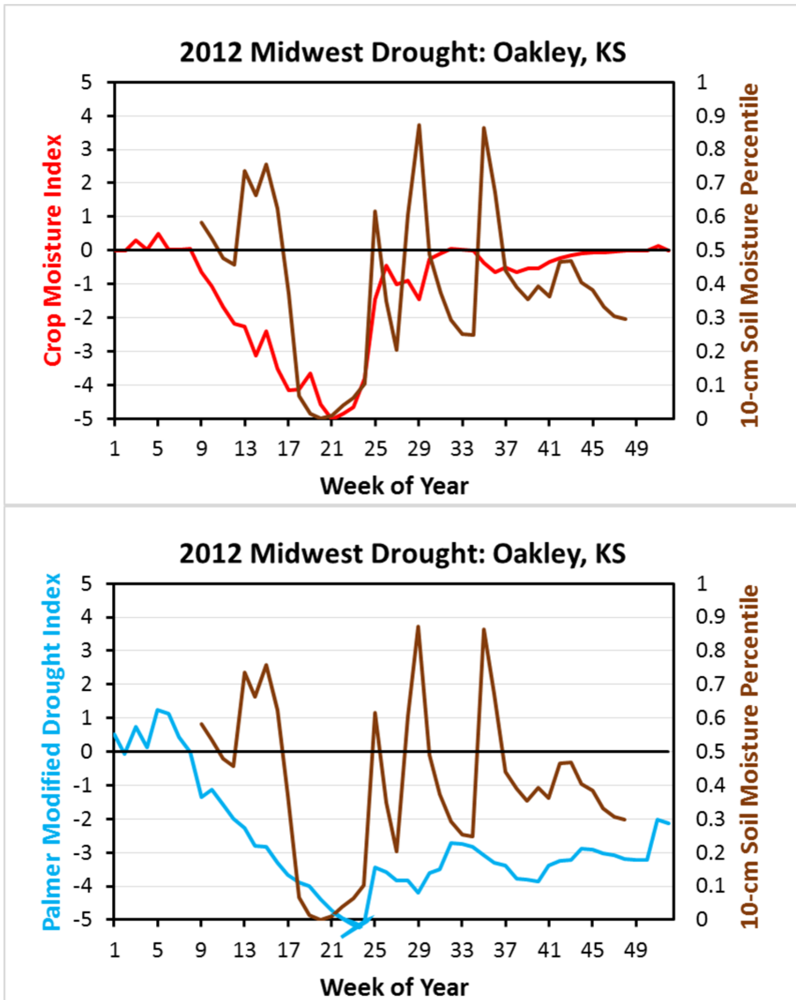


Figure 4. Comparison of Oakley, Kansas 2012 USCRN 10-cm soil moisture percentiles averaged over 7-days with Climate Prediction Center weekly Crop Moisture Index (top) and Palmer Modified Drought Index (bottom) for Kansas climate division 4. The 10-cm soil moisture percentile follows the Crop Moisture Index more closely, as one would expect at a weekly time scale and shallow soil level, but note that its low stands evolve in a manner similar to the much longer time scale of the Palmer Modified Drought Index.

- Beyond percentile averages, percentage counts of the number of hours in a period exceeding certain percentile thresholds are also being studied for their efficacy as drought indices. These seem to be very promising for detecting drought initiation (Fig. 4).

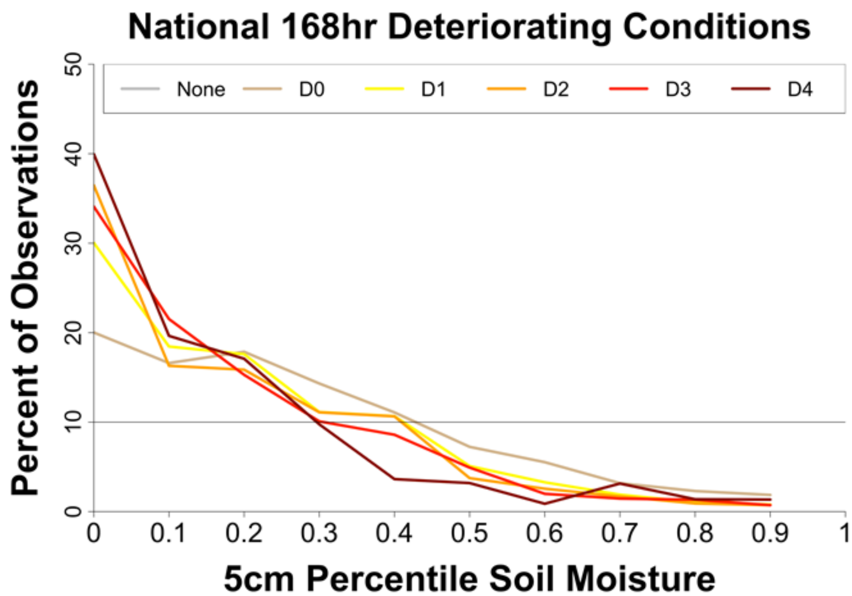


Figure 5. Percent of hourly observations at a given 5cm soil moisture percentile level during weeks when there is deterioration of U.S. Drought Monitor categories from nothing to D0, D0 to D1, D1 to D2, D2 to D3, and D3 to D4. These are results combined from all USCRN stations in the conterminous U.S.

While the effort in the drought indices subproject is promising and ongoing, the expected publication has been delayed by the departure of Dr. Jesse Bell in June. This work will continue into FY19, as will the transition of these beta products to operational products that will be updated in near real time for use by USDM authors and other user communities. The goal of this work continues to be to support the application of in situ soil moisture observations to drought monitoring and other applications through quality controlling and standardizing raw observations and converting them to useful indices.

Climate Monitoring Highlights

Hot and Dry: Summer 2018 at Stovepipe Wells

The average air temperature for June-July-August (JJA) 2018 was 102.4°F (39.1°C), which was higher than the previous two record years in 2017 and 2016 (Figure 6). This was also the driest summer in the station record, with only 0.02 inches (0.4 millimeters) of precipitation that fell on the last day of July.

The importance of these temperature observations recorded at the USCRN station (Figure 7) was that they could be used as a reference to verify the warmest summer average air temperature (104.2 F or 40.1 C) ever observed at the nearby NOAA NWS Cooperative Observer Program (COOP) Network station in Death Valley (Figure 7). This station near Furnace Creek, California, is in a lower and warmer part of Death Valley at -194 feet (-59.1 meters) elevation relative to mean sea level, while the Stovepipe Wells station is at +84 feet (+25.6 meters). Adjusting for the elevation difference between the two stations, the two temperature values were very similar. This could potentially be the warmest JJA summer ever recorded on earth at a reliable observation station, and may also be the first time summer average air temperature was observed to exceed 104°F (40°C). High quality reference measurements will contribute to the analysis and confirmation of this event.

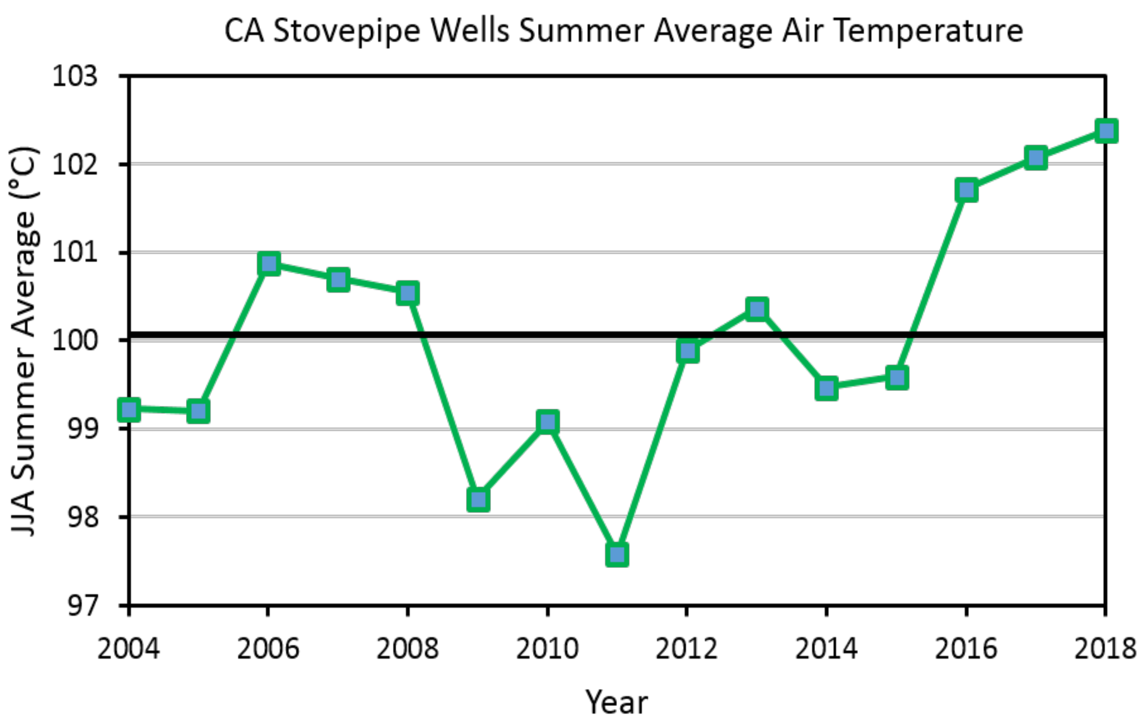


Figure 6. Summer average air temperature at the U.S. Climate Reference Network station near Stovepipe Wells, California from 2004 to 2018. Summer 2018 was the warmest on record.

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Figure 7. USCRN Station at Stovepipe Wells, CA

Warm and Wet: August 2018 at Hilo

The hurricane season in the central North Pacific was unusually active this year, with the Hawaiian Islands impacted by an unprecedented pair of tropical storms approaching from the eastern Pacific, Hurricane Lane and Hurricane Olivia. Of these, Lane had the greatest impact, drenching the Big Island of Hawaii with enormous rain bands for several days as the storm slowly approached and then stalled south of Oahu August 22-26. This compounded a month of August that was already very warm and wet in the Hilo area. At the USCRN station near Hilo, a 4-day rainfall total of 47.61 inches (1209.2 millimeters) was recorded from August 22 to August 25. (Figure 8.)

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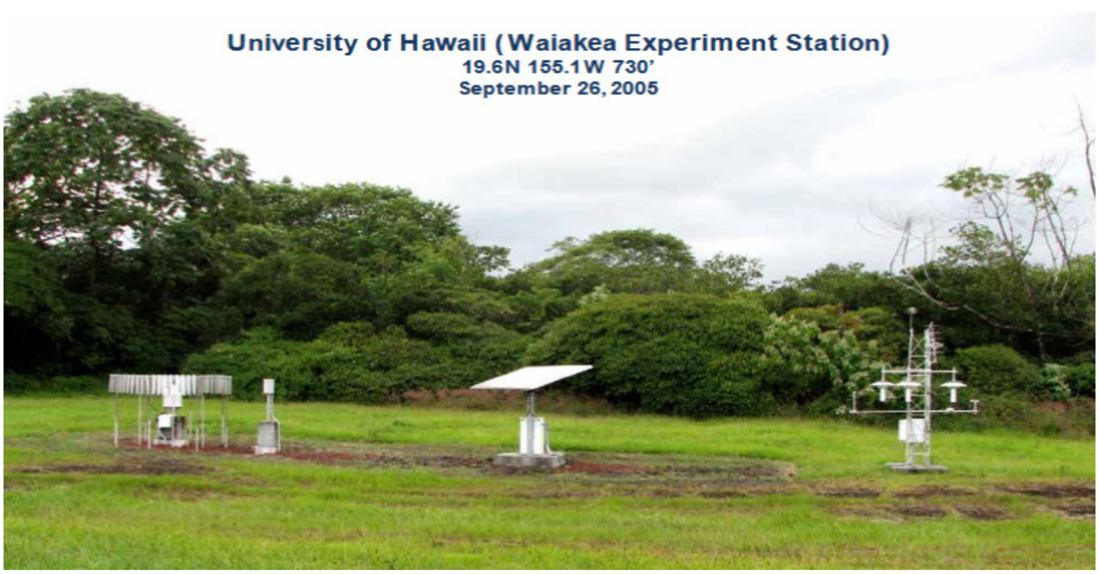

Figure 8. USCRN Station at Hilo, HI.

To place this in perspective, this amount was similar to those measured in the Houston area during

Hurricane Harvey In 2017 and in the Wilmington area during Hurricane Florence this year. Looking at how the rain accumulated over these days at 5-minute increments (Figure 9), it is easy to see when the heavier rain bands passed over the site.

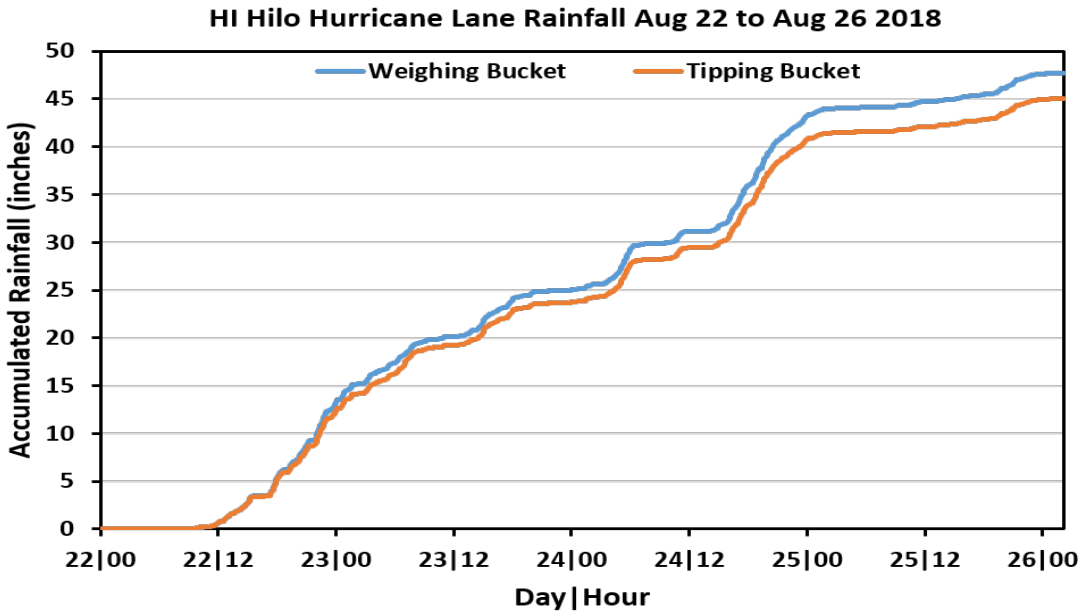

Figure 9. Rainfall accumulation at 5-minute intervals at the U.S. Climate Reference Network station near Hilo, Hawaii, during the Hurricane Lane event August 22-26, 2018. The official rainfall record for the station is measured by the weighing bucket gauge (blue line); the tipping bucket gauge (orange line) cannot keep up with the rainfall rate at times of great intensity.

Looking at this in context, the Hilo area of Hawaii has a wet climate due to its coastal location facing the north easterly trade winds in the tropical Pacific, especially in the fall and winter months. August is usually not considered part of the wet season, with the previous 12 August amounts recorded at the Hilo station averaging 11.27 inches (286.3 millimeters). During August of 2018, the USCRN Hilo station received a staggering 67.10 inches (1704.4 millimeters), the largest calendar month total ever recorded at any USCRN station. Hilo also set a new network-wide 30-day record of 67.35 inches (1710.6 millimeters) between July 30 and August 28. However, it was the shorter duration rainfall totals around the time of Hurricane Lane's passage that were most unusual. Using statistics from many other stations on the Big Island over the last century, one can estimate how often rain totals of this size would occur. The values below are the estimates resulting from Hurricane Lane at the USCRN Hilo station:

7-day: 1305.6 mm (51.40 in) 200-year return interval
4-day: 1215.6 mm (47.86 in) 500-year return interval
3-day: 1124.6 mm (44.28 in) 750-year return interval
2-day: 812.6 mm (31.99 in) 200-year return interval
1-day: 501.2 mm (19.73 in) 50-year return interval

While these are lengths of time in days, the "day" may start and end at any 5-minute period, thus capturing the biggest possible rain amount for each interval tested. In addition, these statistics are based on year-round precipitation histories, so the likelihood of having these events in the relatively dry month of August is even more unusual. The 3-day and 4-day rainfall amounts were the most unusual. A 500-year return interval means that there is a 0.2% chance of this occurring in any given year. A 750-year event has a chance of occurring only slightly above 0.1% in any given year. The ability of the USCRN station to function accurately during such extreme events is a testament to its design and engineering.

It is also of interest that the other USCRN station on the Big Island of Hawaii also broke their station August total and total for any month with 13.20 inches (335.3 millimeters). The previous August record was 7.70 inches (195.6 millimeters) and the previous record for any month was 9.67 inches (245.7 millimeters) set in December 2016. That site is located over 11,000 feet above sea level on the North slope of Mt. Mauna Loa. Even though the Hilo site and surrounding lowlands on the windward side of the Big Island experience many heavy rain events, it is rare when any of those events bring much rain to the high elevations where the Mauna Loa site is located (Figure 9). Given the above statistics the two tropical storms that affected Hawaii during August 2018 was a significant exception.

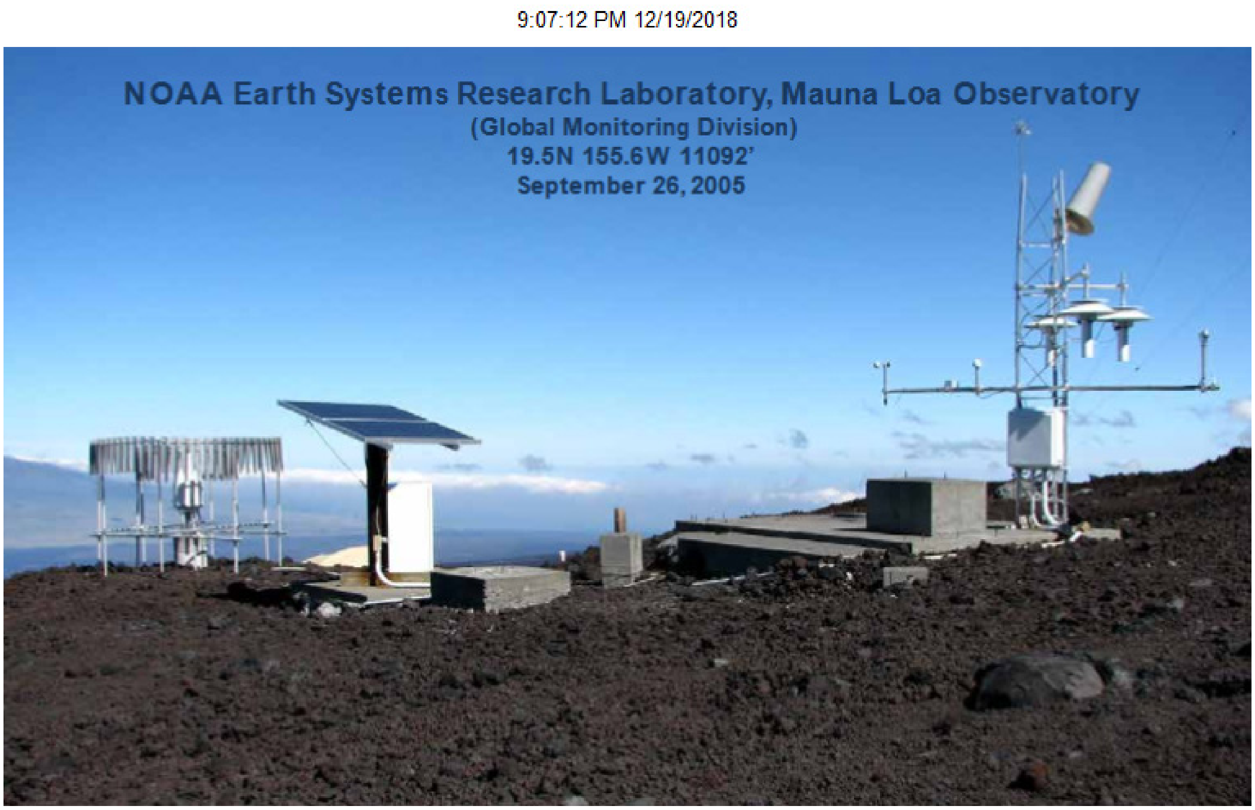

Figure 9. USCRN Station at Mauna Loa, HI.

Plans for FY19

A number of long-term science projects will continue or commence during FY18:

FY2019 Plans for USCRN Science at NCEI

The NCEI activities related to USCRN soil moisture observations and drought are aligned with the requirements set forth in NIDIS Public Law (P.L. 109-430) Goal 1 to enhance NIDIS functionality through the provision of data supporting the assessments of the severity of drought conditions (Activities 1, 2, and 3). USCRN work plans continue also to address the fourth goal of NIDIS promulgated in the 2014 reauthorization law (P.L. 113-86) to use in situ soil moisture measurements to characterize the length and severity of drought. USCRN will continue work transitioning beta products developed in FY18 to operational products updated in near real time for use by USDM authors and other user communities. Finally, the applicability of the methodologies developed to date for standardizing in situ soil moisture observations will be extended to satellite estimates of soil moisture. The goal of this work continues to be to support the application of soil moisture observations to drought monitoring and other applications through quality controlling and standardizing raw observations and converting them to useful indices.

Activity 1: Soil Moisture Operations and Transition to Near-Real-Time Index Production

Quality assurance and validation of the past month's in situ soil moisture observations will continue to be accomplished through manual review and analysis.

The work being performed to support the analysis of the Acclima soil moisture probe will continue. This activity will also be expanded to an assessment of the continuity of the soil moisture observations from the legacy Hydra to the new Acclima probes.

As is the usual practice, USCRN soil moisture data will be provided to the National Soil Moisture Network (NSMN) and NASA SMAP. The NCEI USCRN Team also will continue to participate in quarterly USDA soil moisture conference calls, NASA SMAP calls, soil moisture application conferences, and NSMN meetings. Mr. Ronald Leeper of the NCEI USCRN Team and lead scientist Dr. Michael Palecki will directly represent our NIDIS efforts to NSMN, NASA, and the USDA.

The transition of the standardized soil moisture indices and drought indices (developed in FY18) from beta products to NCEI operational products will be completed and the products will be generated in near-real time for the benefit of U.S. Drought Monitor authors and other user applications. This transition requires software development to convert scientific code to a stable and easily maintained software system, and will include release of the final form of the drought indices as developed in Activity 2 during FY19.

Activity 2: Development of Drought Indices Based on In Situ Soil Moisture Observations

- The three year, multi-person effort to construct the standardized soil moisture data set and drought indices derived from these data will be completed in FY19. A series of soil moisture-based metrics that inform the state of hydrological conditions and are under examination include:
- Soil Moisture Anomalies and Percentiles, and
- Percentage Counts of Percentile Exceedances.
- These metrics are being tested over various lengths of time and soil layer depth integrations, including the top layer (5-10 cm), root layer (5-20 cm) and total column (5-100 cm).
- The work associating combinations of standardized soil moisture threshold exceedances at

various soil depths with existing drought indices such as PMDI, PHDI, SPEI, etc., is underway already. Especially important is the determination of how soil moisture data can best be used to provide information to drought assessment that is either contributory or unique when added to other drought status indicators.

- A publication will be submitted based on this work substantiating the utility of the final choices of operational drought indices.
- Work to be presented at the December 2018 AGU Meeting in Washington, D.C.

Activity 3: Application of Standardization Methods to Satellite Soil Moisture Estimates
Previous research indicates that modelled and satellite remotely sensed soil moisture estimates are utilized for many applications as absolute values of volumetric soil moisture. However, just as in the case of in situ observations, standardized soil moisture data is highly applicable for drought monitoring and many other activities. The methods developed be the NCEI USCRN Team for in situ observations will be studied for their applicability to satellite observations.
A project has been started to test this approach using the relatively lengthy AMSR-E soil moisture time series that overlaps with two years of the USCRN in situ observations. The full length AMSR-E period-of-record will be sufficient for the sampling and standardization approach, and its efficacy will be tested against the overlapping standardized in situ observations.
If this exploration proves to be successful, the approach can then be applied to ongoing satellite soil moisture collection systems such as SMAP in FY20.
Leeper will present preliminary results of this effort at the 5th Satellite Soil Moisture Validation and Application Workshop this October in the Washington D.C. area.

FY19 Deliverables for NIDIS
Operational quality control of soil moisture observations and support to Acclima probe study.
Completion of drought indices development and submission of a journal article.
Release of operational standardized soil moisture data and drought indices.
Application of standardization methodologies to satellite soil moisture estimates.

Data and software infrastructure are continuing to evolve and improve according to long-term plans:

- Improvements continue to help facilitate the access to USCRN data and products for users.
- Work continues in incorporating changes to GOES ID numbers as part of the CS1 to CS2 GOES transmitter transition that began in 2016 and that must be completed network-wide by 2025.
- Continued implementation of changes to the database and ingest systems to incorporate new soil elements as part of the soil sensor upgrade effort.

Hardware testing and deployments will continue:

- One new station will be deployed in Alaska during the summer 2019 building season, which will bring us closer to the eventual final total of 29 stations across Alaska. The site to be installed is in Bethel, AK, which begins the program's effort to populate the more sparse western areas of the state with USCRN stations.
- As many stations enter their second decade of service, the routine implementation of a

refresh of critical equipment at stations around the network include the need for new back-up batteries, improved solar panels, replacement of soil sensors, and repairs to precipitation shield fencing.

USCRN continues to play a larger role in monitoring U.S. climate change as it has entered its second decade of service; and the challenge is to continue the high level of performance and data receipt rate that are being taken advantage of by more and more users.