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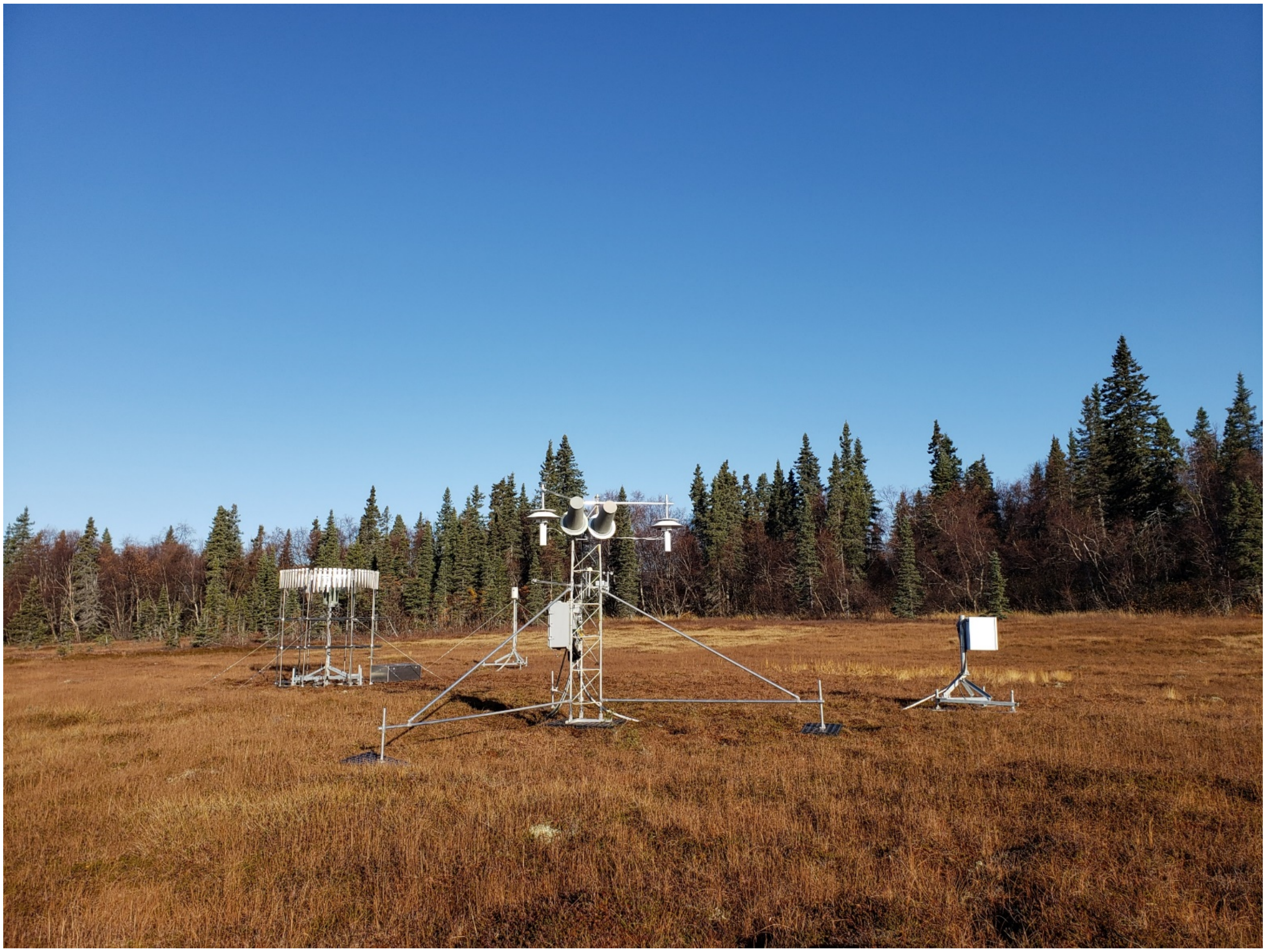
US Climate Reference Network



Annual Report for Fiscal Year 2019

Compiled by the
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Cover Photo:
Photo of the new USCRN station in Aleknagik, Alaska; installed in September 2019. (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

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Michael Black, Michael Buban, Scott Embler, Brent French, Grant Goodge, Mark Hall, Bryan Iddings John Kochendorfer, Ronnie Leeper, Tilden Meyers, Michael Potter, Jared Rennie, Mike Rutherford, Barbara Shifflett, Devin Thomas, Kristy Thomas, and Tim Wilson

Preface and Introduction

During Fiscal Year 2019, the U.S. Climate Reference Network (USCRN) continued to make significant progress under the auspices of NOAA's Air Resources Laboratory (ARL) with cooperation and collaboration from NOAA's National Centers for Environmental Information (NCEI). The network consists of 114 stations across the conterminous 48 states, 23 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 FY2019

1. **Continuing to Push past the Halfway point in Alaska**
   In FY19, one new station was installed in Alaska (a) in Aleknagik, AK, in the southern portion of the state. This brings the network configuration in the state up to 23 out of a planned total of 29 stations by FY2024.

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 FY2020 and COVID-19

FY2019 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 7 stations by the end of FY2022.

Site Licenses Signed: One site license was completed for Alaska (Aleknagik) in FY2019, with several others in progress.

Stations Installed: One new station (Aleknagik) was installed in Alaska in FY2019.

Stations Commissioned: One station (Bethel) was commissioned in Alaska in FY2019.

In addition to the station installed in FY2019 at Aleknagik, three additional sites are licensed and pending installation (Kodiak, Galena, 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 and Aniak Traditional Council at Aniak.

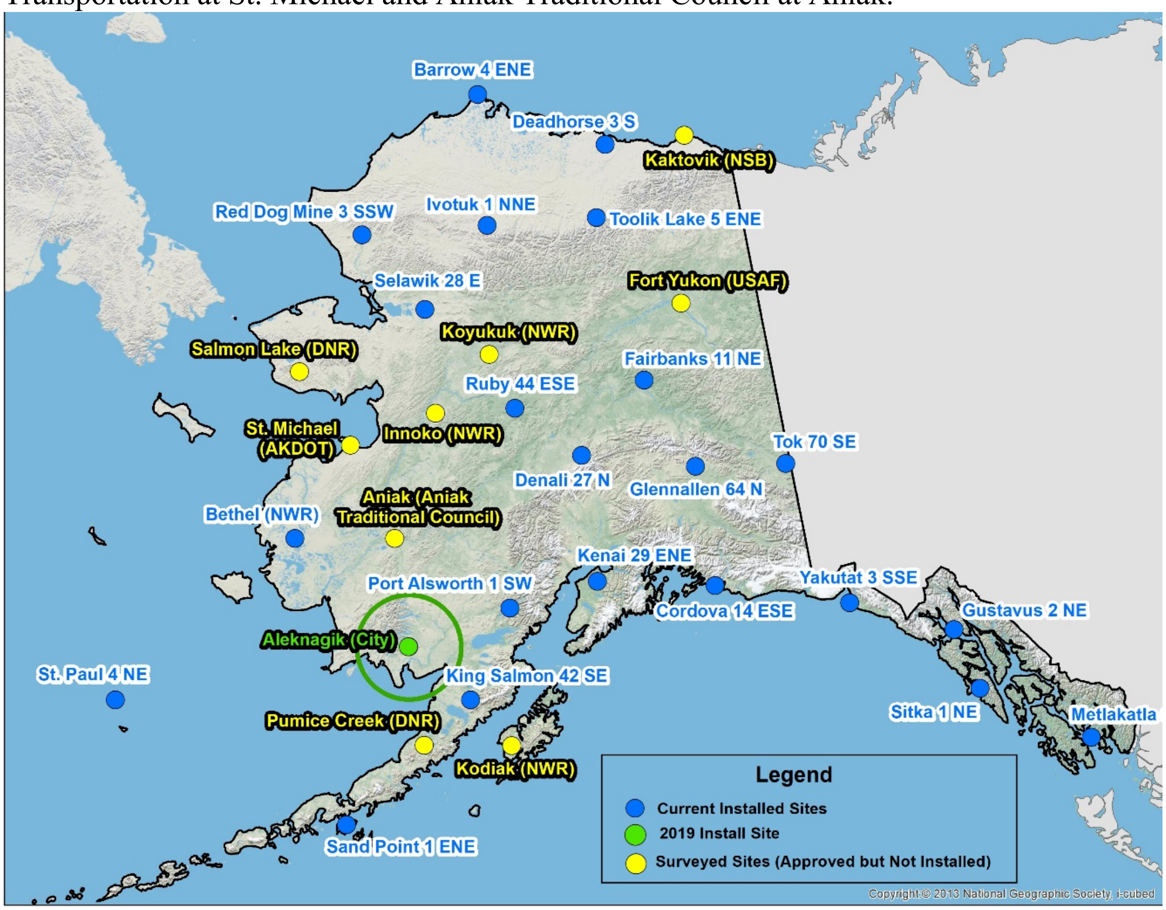


Figure 1. The Map of USCRN stations in Alaska – existing and planned sites.

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%
2019	22	83.1%	82.6%

Table 2. USCRN in Alaska Data Receipt Rates (%) for FY2019 by Quarter[1]

	Within 30 days	As of 9/30/19
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**

[1] **The overall data receipt rate for the entire USCRN (including the stations in Alaska) was 99.6% (see Table 4) which is above the performance measurement standard of 98% across the entire network.**

Table 3. FY2019 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	9/2019
Aleknagik (City of Aleknagik)	04/16/2019	10/2019	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 (Aniak Traditional Council)	Pending	TBD	TBD

FY2019 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 FY2019 by Quarter (including Alaska)

	Within 30 days	As of 9/30/19
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 FY19. The year included the departure of one of USCRN's two outstanding software developers. Fortunately, another equally proficient developer was brought on board with a period of overlap for cross-training. The team continued to perform at a high level, and as in previous years, high uptime rates were maintained through ongoing systems monitoring 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, completing website and IT structural upgrades, and making other improvements as discussed below.

Other Quality Control and Processing Improvements

The USCRN processing system includes a set of quality control checks that identify and flag measurements as invalid when they exceed pre-established quality control threshold limits. There are also instances when equipment malfunctions or other issues cause data to be erroneous, even though the values fall within the range of acceptable values. In such cases, because the inaccurate measurements are not flagged by the automated quality control algorithms, a process based on manual intervention is used to flag the faulty data values.

This involved periodically flagging data due to faulty instruments (or unflagging data once instrumentation was fixed), deploying changes to production, generating a script to re-QC changes retroactively, communicating with scientists/engineers, and verifying results.

Examples of issues identified through this process include the following:

- Identified quality control issue for Champaign, IL precipitation and provided plots/analysis to USCRN
- scientists and engineers. Deployed final agreed upon changes to production.
- Identified anemometer issue at Newton 8, GA station.
- Identified issue with precipitation at Port Aransas, TX station; notified team to check for QC/instrument issues.
- Completed flagging of Alaska false precipitation readings identified by USCRN scientists.

Traditionally, flags such as these have been applied using the ingest software's "bad sensor list", which is then applied to the USCRN database and further verified by the QC specialists.

Improvements to this process that began in 2018 were completed in FY19 and used throughout the latter part of the year. The work involved implementation of a web interface that allowed the quality control specialists to more easily identify and flag invalid observations. This was combined with revisions to the Ingest software to allow for automated reprocessing of observations whenever quality control issues were identified via the web interface. The web interface allows users to search for previously entered quality control issues, edit those issues, or record new quality control issues. Each issue that is entered allows users to specify which stations, sensors, and time periods are affected as well as the quality control flag that will be applied to the data. Manually specified flags are applied immediately by the ingest process, allowing past and future data to be flagged consistently. Along with these manual quality control features, numerous performance improvements were made which allow multiple data files to be ingested and existing data to be refreshed simultaneously.

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). Each month quality control work was completed for more than 1000 soil sensors; including preparation and manual assessment of hundreds of diagnostic plots to identify possible issues. QC flags were either set or removed and post-QC plots were analyzed to verify results.

Final software changes also were completed for the new "SOIL01 product", incorporating changes requested by scientists/engineers, completing the README file, and deploying on test and production servers. Files are now available at ftp://ftp.ncdc.noaa.gov/pub/data/uscrn/products/soil01/, providing hourly soil moisture and temperature observations, precipitation, temperature and wind speed and direction. This fulfilled a task established at the FY18 NCEI-ATDD meeting in Oak Ridge.

Support for Analysis of New Acclima Soil Sensors
To support the analysis and assessment of the performance of new Acclima soil moisture sensors, plots and analysis were produced each month for Acclima soil probes at ten test stations. This included populating spreadsheets to provide a summary of the behavior for all soil moisture and temperature sensors at each station, as well as the station's month-to-month behavior with cumulative flag counts. Plots were prepared showing dielectric/volumetric/precipitation for particular stations of interest, and a PowerPoint of the results provided for discussion during USCRN team monthly reviews.

Other activities associated with the Acclima installations and analysis included the following:

- Analyzed all soil sensor behavior (past and present) for replacement potential to Acclimas at numerous stations.
- Wrote SQL query to more easily identify when newly installed Acclima sensors were brought on-line.
- Temporarily flagged dozens of Acclima sensor installs as they were added.

- Created shared spreadsheets to help team track installs.
- Coordinated with ATDD regarding past and upcoming AMVs and soil sensor replacement plans.

Our software developers also supported the USCRN scientists in preparing for an upcoming comparison of the new Acclima soil probe measurements against the legacy Hydra probes in order to further assess the performance of the new probes. Analyzing the differences will require removal of flags that were put in place to prevent Acclima probe data from entering the quality-controlled products. All Acclima measurements are flagged upon installation so that they cannot be used to calculate volumetric soil moisture until they are deemed to be operational. In preparing for the comparisons, which will take place in FY20, USCRN developers and scientists coordinated to identify the optimum method for removing Acclima flags and calculating volumetric soil moisture. These preparations also included completing a copy of the soil dataset.

The developers also provided support for the effort to develop the standardized soil moisture product, which began in 2018. After USCRN scientists completed development of the approach for standardizing soil measurements, the scientific code was converted into a system suitable for robust and repeatable operational production of soil climatologies and departures. The product schedule includes a Beta release in early FY20 followed by a final release in late FY20 or early FY21. Subsequent analyses will include a review of the differences in the standardized soil moisture values between the Acclima and Hydra sensors.

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 extracting sub-hourly tipping bucket values and computing hourly values for all stations for a two-year period for the University of Oklahoma-CIMMS. Completed 'crnscript' Python module for processing period-of-record tipping bucket values and other variables for 11 stations for the South Dakota State Climatologist. Supported OAR/ATDD with several data extractions including hourly soil variables along with solar radiation, surface IR temperature, and 5-min precipitation, wire depths, wetness, wind speed, temperature and diagnostic variables for the Boulder, CO station. Also reformatted all USCRN period-of-record sub-hourly products files for researchers at USDA/ARS in Tucson, AZ.

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. This included verifying that all data files (5 USCRN datasets) were archived properly for the month, including confirming that the contents of all monthly tar files with datalogger/PDA records (1st-order data) were complete. Verified contents of archived datalogger (PDA tar files) for all months for 2013-2018. Worked with Archive Branch and Data Operations Branches personnel to fix issues, including archiving missing PDAs, and reconciling inconsistent and incorrect filenames. Submitted a Request to Archive document for new Standardized Soil Moisture product; https://www.ncdc.noaa.gov/atrac/export/2018-11-29T17-16-28.pdf?id=52369. Also worked with Archive Branch to update CRN's submission agreement due to termination of Tiksi, Russia data collection.

DOMSAT to HRIT Transition

Until FY19, the USCRN processing system used the Domestic Satellite (DOMSAT) system as a backup data source for the GOES DCS data stream. With NESDIS plans to discontinue DOMSAT in May 2019, NCEI's receiving satellite dish and associated system were replaced by the Microcom Environmental DAMS-NT with support from the USCRN developers. The replacement of the existing satellite dish and the receiver and converter appliance with an HRIT (High Rate Information Transmission) compatible system was performed in the first quarter of FY19. The HRIT broadcast is provided from the GOES satellites and carries the DCS data stream among many other data types. The new equipment included the necessary satellite dish as well as the server for receiving, decoding, and distributing the HRIT data stream.

Before the end of FY19, short-notice advisement of needed changes to the GOES HRIT data stream format necessitated a firmware upgrade to the new DigiRIT receiver. Microcom Environmental supplied the binary file which the Developers used to successfully upgrade the receiver. During the time that receiver was offline, the USCRN's backup acquisition systems continued to collect and ingest observations from Wallops Island and the Emergency Data Distribution Network. All station observations were acquired and there was no operational impact.

Station Name Change

An update to metadata for the USCRN station at Utqiaġvik, AK (formerly Barrow) was performed to include the correct diacritic above the 'g' character in the station name. To accomplish this, edits were made to ISIS metadata and the USCRN products and website software were updated to handle the UTF-8-character set, which greatly expands upon the ASCII character set and includes the necessary diacritic character that made this update possible.

Website Changes

Maintenance of the USCRN website in FY19 included numerous enhancements. ATDD engineers requested adjustments to reports and charts, and many improvements were made to the website's theming and organization. This included updates to the sensor page, which is the most frequently used page on the site. It was upgraded to provide easier links to charts and cleaner table layouts for each of the sections shown. Monitoring was also increased to determine when load changes would result in the website becoming unavailable. This enabled developers to quickly request a correction by staff in NCEI's IT Services Division, who would diagnose the problem and promptly restart the web server.

NCDC Wiki Retirement

For over a decade the USCRN developers had access to an NCEI wiki system, which they used to record and maintain a large number of details about software development, operations and associated policies. Unfortunately, this wiki system had grown outdated and could no longer be maintained by NCEI's IT staff. As a result, the wiki was decommissioned. In preparation for its end-of-life, USCRN developers exported a static copy of all of the wiki's entries to a separate internal web server. This preserved a valuable record of past activities and the evolving nature of the USCRN project, along with records from other groups such as ISIS and HOMR metadata.

CS2 Transmitter Migration

An upgrade of the USCRN satellite transmitters from CS1 to CS2 which began in FY18 continued in FY19. 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. Updates to the USCRN database and Ingest software were made previously to map a GOES platform identifier to the correct station based on the timestamp of a received transmission. This enables ATDD engineers to install the new transmitters and assign new platform identifiers without the possibility that more than one GOES platform identifier would be associated with a station.

In FY19 USCRN developers continued to coordinate with ATDD engineers and field technicians for each upgrade to ensure that all possible observations were collected for each station which had its transmitter upgraded. Additionally, the Ingest software was updated to provide a 12-hour window where old and new GOES IDs were recognized for a station, allowing engineers more flexible scheduling of their site visits and station maintenance.

Virtual Environment and Storage System Migrations

At the direction of NCEI's IT Services Division, USCRN developers migrated to a newer virtual machine platform, oVirt. This migration was necessary to ensure that NCEI-NC would continue to comply with evolving security and maintenance requirements. The development, integration, and production tiers were migrated in sequence with minor corrections to configuration being required. After the successful migration the virtual machines operated continuously until a hardware failure in NCEI's shared storage system took them offline. USCRN developers coordinated with ITSD to move off of the shared storage system, and after the second migration was completed in early September, the USCRN's operations experienced no further interruptions.

Migration to Git/GitLab for Project Source Code Management

NCEI's IT Services Division directed that all software projects migrate from the code repository Subversion to Git in FY19. The USCRN developers completed this migration, and are able to take advantage of the more advanced features provided by Git and GitLab for software development. Along with this migration the continuous build server, Jenkins, was also upgraded to use Git and build pipelines. This allowed developers to build and maintain branches more easily than what Subversion allowed, and significantly simplified the configuration of Jenkins.

Eclipse to IntelliJ and OWASP Dependency Check Integration

USCRN developers switched Integrated Development Environments, from Eclipse to IntelliJ. This switch opened up many new possibilities with the assistance of better tooling that IntelliJ provided, as well as the better integration with supporting technologies like Maven, Ivy, Git, and Ant. Making use of these features, developers were able to streamline build and deployment systems through Jenkins, and establish a base project configuration that all projects would use.

With the introduction of Jenkins pipelines, it was possible for developers to integrate OWASP dependency checks into the build process. This ensures that developers are aware of any vulnerabilities in the libraries that they use, and prevents severe vulnerabilities from being inadvertently included in the USCRN software system. These checks run automatically as part of the build process and do not require any extra effort from the developers.

<u>USCRN Climate Science and Development Activities in FY19</u>
USCRN Climate Science Team (federal lead Michael Palecki and cooperative affiliates Ronald Leeper and Jared Rennie) made substantial progress in its two primary foci: improving the utility of USCRN soil moisture observations through standardization and drought index development, and producing heat health applications based on USCRN station observations. The team also continues to collaborate with other researchers and groups utilizing USCRN observations, both locally and nationally. Finally, a number of papers under preparation in the FY18 have been published or submitted in FY19:

Prat, O. P., B. R. Nelson, E. Nickl, and **R. D. Leeper**. Global evaluation of satellite based Quantitative Precipitation Estimates (QPEs) from NOAA's Climate Data Records (CDRs). Submitted to **Journal of Hydrometeorology**.

Nelson, B., O. P. Prat, and **R. D. Leeper**. Using Ancillary information from Radar-based observations and Rain Gauges to Identify Error and Bias. Submitted to **Journal of Hydrometeorology.**

Inamdar, A., and **R. D. Leeper**. A novel approach combining satellite and in situ observations to estimate the diurnal cycle of land surface temperatures for all sky conditions. Submitted to **Journal of Applied Meteorology and Climatology**

Wilson, T. B., H. J. Howard, J. Kochendorfer, T. P. Meyers, M. Hall, N. W. Casey, C. B. Baker, R. D. Leeper, M. A. Palecki. Evaluating Time Domain Reflectometry and Coaxial Impedance Sensors for Soil Observations by the U.S. Climate Reference Network. Submitted to **Vadose Zone Journal**.

Leeper, R. D., J. Kochendorfer, T. Henderson, **M. A. Palecki**, 2019. Impacts of small-scale urban encroachment on air temperature observations. **Journal Applied Meteorology and Climatology**, 58, 1369 – 1380. http://dx.dio.org/ 10.1175/JAMC-D-19-0002.1

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 Applied Meteorology and Climatology,** 58, 1417 - 1428. http://dx.dio.org/10.1175/JAMC-D-18-0269.1

The base standardized soil moisture dataset has been revised and published to the USCRN web site as a Beta Product available through 2019, and will be completed with the NCEI approval process and made operational in real time during FY20:

USCRN Standardized Soil Moisture (SSM) Dataset
https://www1.ncdc.noaa.gov/pub/data/uscrn/products/soilanom01/
USCRN Soil Moisture Climatology (SMC) Dataset
https://www1.ncdc.noaa.gov/pub/data/uscrn/products/soilclim01/
Accomplishments of USCRN Soil Moisture and Drought Work

Substantial progress was made on planned activities for USCRN soil moisture and drought indices by Ronald Leeper and Michael Palecki. The development of the standardized soil moisture (SSM) product was completed following reconfiguring and improving the SSM product in response to feedback from partners and journal article reviewers. In addition, we had a NOAA Hollings Scholar to work on drought indices development during summer 2019. Prototype drought indices are currently being evaluated and this work will continue in FY20.

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

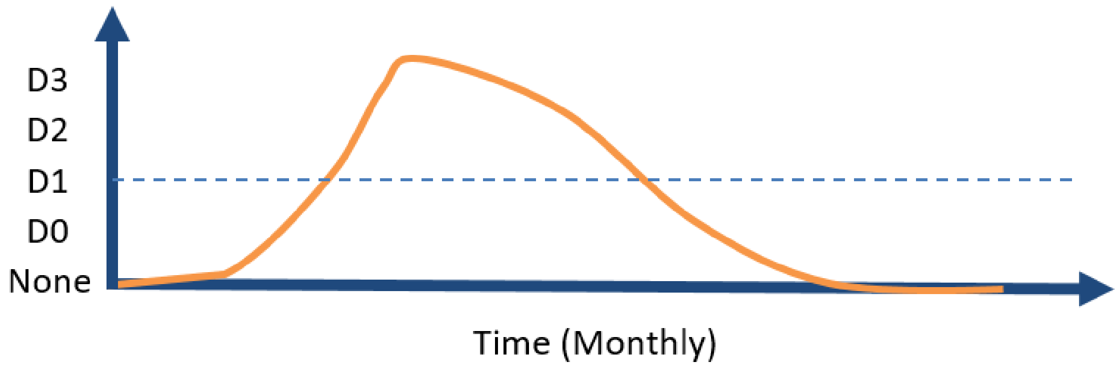
- We continue to provide both automated and manual quality control of the USCRN soil moisture observations. These data are provided to the National Soil Moisture Network, the International Soil Moisture Network, and NASA. Continuous improvement in the QC operations occurred during FY19.
- USCRN developers, working with the soil moisture QC team, improved the system for flagging suspect sensors (including soil sensors), which now has a Web interface to streamline the process.
- Adjustments to the ingest system for the new Acclima probes being deployed in the field went well, and after completion of a study by our instrument science colleagues at ATDD, these soil data (moisture and temperature) will become available FY20. Ronald Leeper and Michael Palecki are co-authors of a journal article submitted to Vadose Zone Journal by Tim Wilson of ATDD: "Evaluating Coaxial Impedance Dielectric Reflectometry and Time Domain Reflectometry Sensors for Soil Observations by the U.S. Climate Reference Network".
- The internal Acclima study is at this link:

https://www1.ncdc.noaa.gov/pub/data/uscrn/documentation/research/NOAA-Tech-Memo-Soil-FINAL-AUGUST%202019.pdf

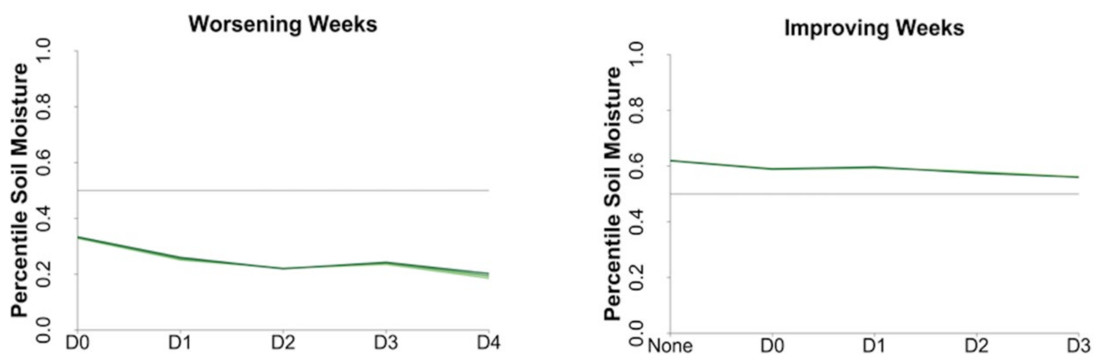
- Ronald Leeper presented on the standardized soil moisture dataset to the USDA Soil Moisture Working Group and Climate Prediction Center (CPC) drought forecast group in June 2019 via telecom. Michael Palecki and Ronald Leeper continued to support the activities of NSMN, USDA, and NOAA partners, and other scientific organizations.

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

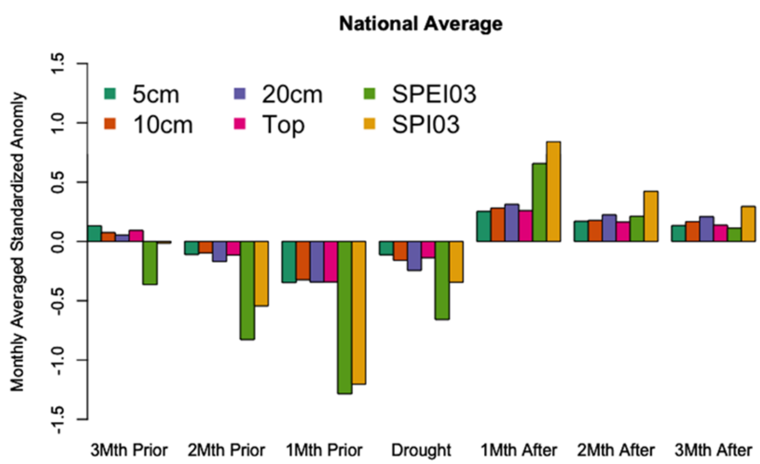
- The work on drought indices commenced as scheduled during FY19. Preliminary results were presented by Michael Palecki at the 2018 AGU Fall Meeting in Washington, D.C., in December 2018 entitled: "Using Standardized Soil Moisture Indices for Drought Monitoring", and Ronald Leeper at the National Soil Moisture Network Workshop during May 2019 in Manhattan, KS, in a presentation entitled: "Evaluating the Linkages Between Soil Moisture and Drought".
- A definition of drought events based on the USDM was developed by Ronald Leeper, requiring moderate drought (D1) to be reached and at least several weeks of no-drought status before and after the event.



- Once a drought event is identified, the standardized soil moisture status during worsening and improving periods are starkly different. However, the worsening response is stronger.



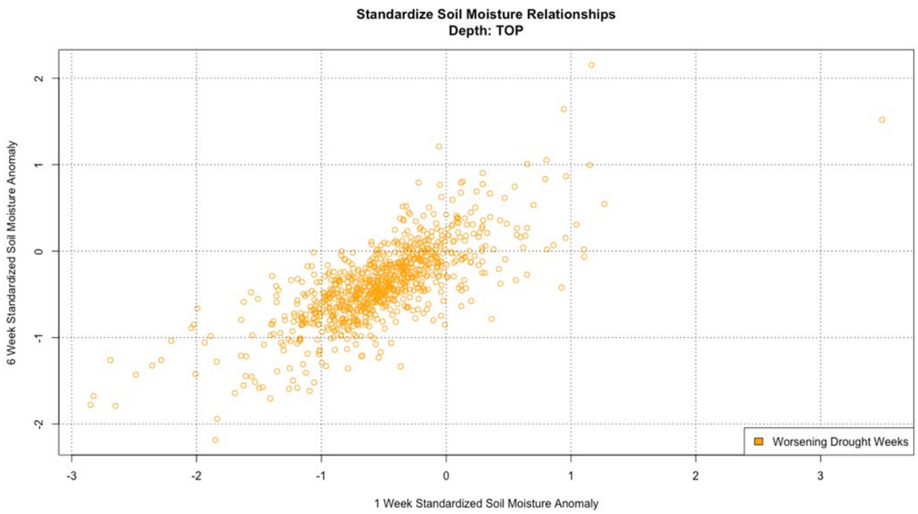
- This was also shown to be true for well-known drought indices SPI and SPEI. The strongest response of these drought indices and standardized soil moisture is in the month prior to the drought event.



- Ronald Leeper presented these results at the first National Soil Moisture Network Meeting in May 2019 in Manhattan, Kansas.
- During Summer 2019, Michael Palecki and Ronald Leeper mentored a NOAA Hollings Scholar from the University of Nebraska, Bryan Petersen. He continues this work with

drought events to evaluate differing drought states, especially onset. His end-of-internship presentation in Silver Spring, Maryland, was entitled "Evaluating Drought Using In Situ Soil Moisture Observations".

- Petersen's work suggested the use of combinations of simple indices over shorter and longer time scales could improve drought detection. For example, onset weeks were very likely to have both negative 6 week and 1-week standardized soil moisture tendencies.



- Variables of interest were generated for USCRN stations and temporally aligned with USDM weekly periods:
  - Averaged standardized soil moisture anomalies (1 to 8 weeks)
  - Averaged soil moisture percentiles (1 to 8 weeks)
  - Standardized soil moisture anomaly trends (4-8 weeks)
  - Percent of percentile threshold exceedance counts (1 to 8 weeks)
- Principal Component Analysis was used to identify the soil moisture variables with the most potential to provide independent explanation of USDM status.
- Some of these combinations were shown at the USDM Forum in Bowling Green, Kentucky, during September 2019. The weeks with counts of sub-30th percentile standardized soil moisture corresponded strongly to intensified drought or maintained drought status (panel b on next page).
- Work on the final suite of drought indices based on standardized soil moisture is ongoing and will be complete during FY20.

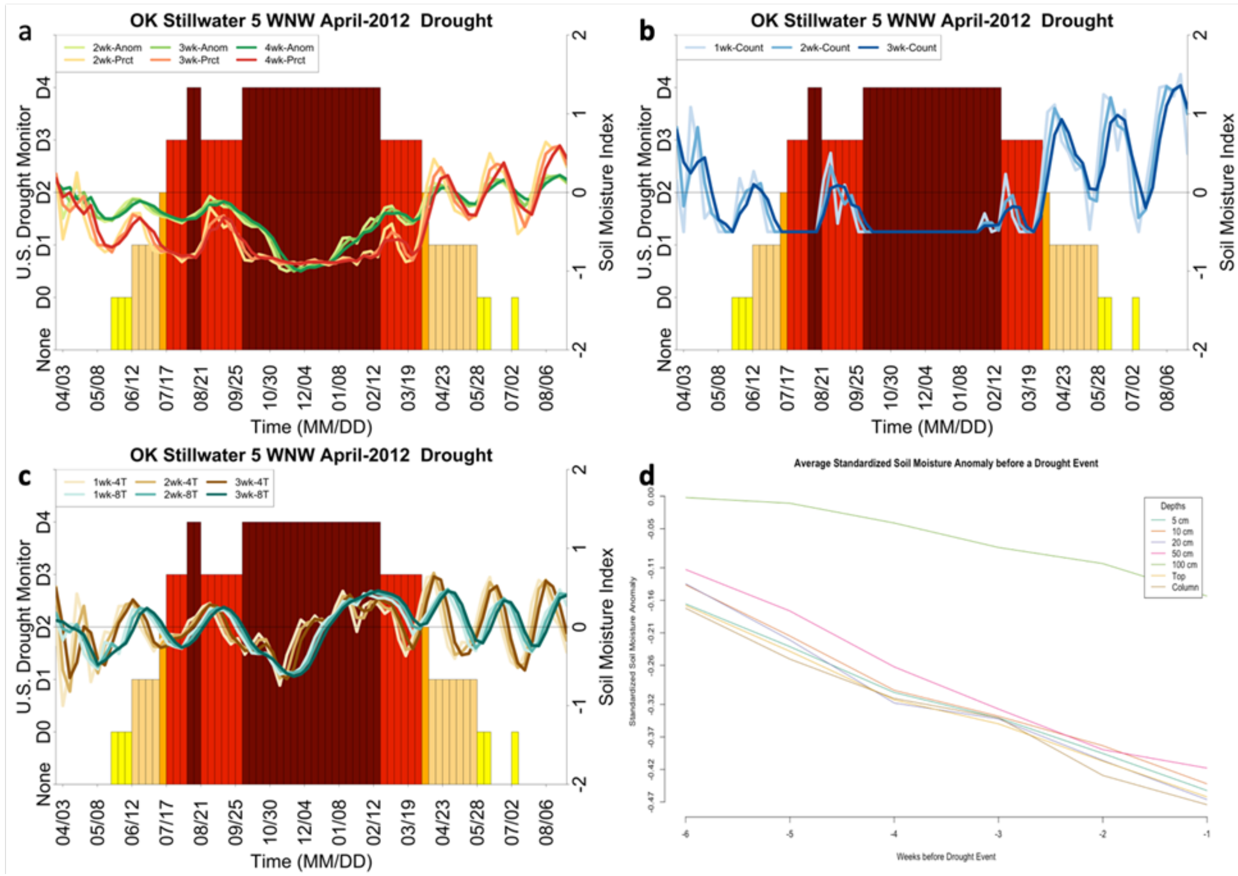


Figure 2. USCRN weekly (a) anomaly percentile averages, (b) percent of 30th percentile exceedance, and (c) anomalous trends for the 2012 drought event at the Stillwater 5 WNW, OK station and (d) national 1-week soil moisture anomaly average 6 weeks prior to all USCRN drought events (since 2008) for all depths.

Activity 3: Application of Standardization Methods to Satellite Soil Moisture Estimates

- Ronald Leeper presented a poster at the SMAP CAL/VAL Workshop #9 and gave a presentation at the 5th Satellite Soil Moisture Validation and Application Workshop in October 2018 on "Standardizing Short-Term Satellite Soil Moisture Datasets". He presented the approach developed for standardizing the relatively brief USCRN soil moisture records and showed an initial application to AMSR-E soil moisture data. The soil moisture variance captured by this satellite was not of the same magnitude as the variance measured by surface in situ soil moisture instruments. His work did demonstrate the importance of standardizing ascending and descending orbit observations separately (see dashed line in figure on the next page).
- Because of the overall low variance nature of the AMSR-E soil moisture observations, it was decided to continue this work using another satellite product; the Soil Moisture Operational Products System (SMOPS) is being considered but has not been released yet. However, the Copernicus Soil Moisture Data Set is available and may be used in FY20.

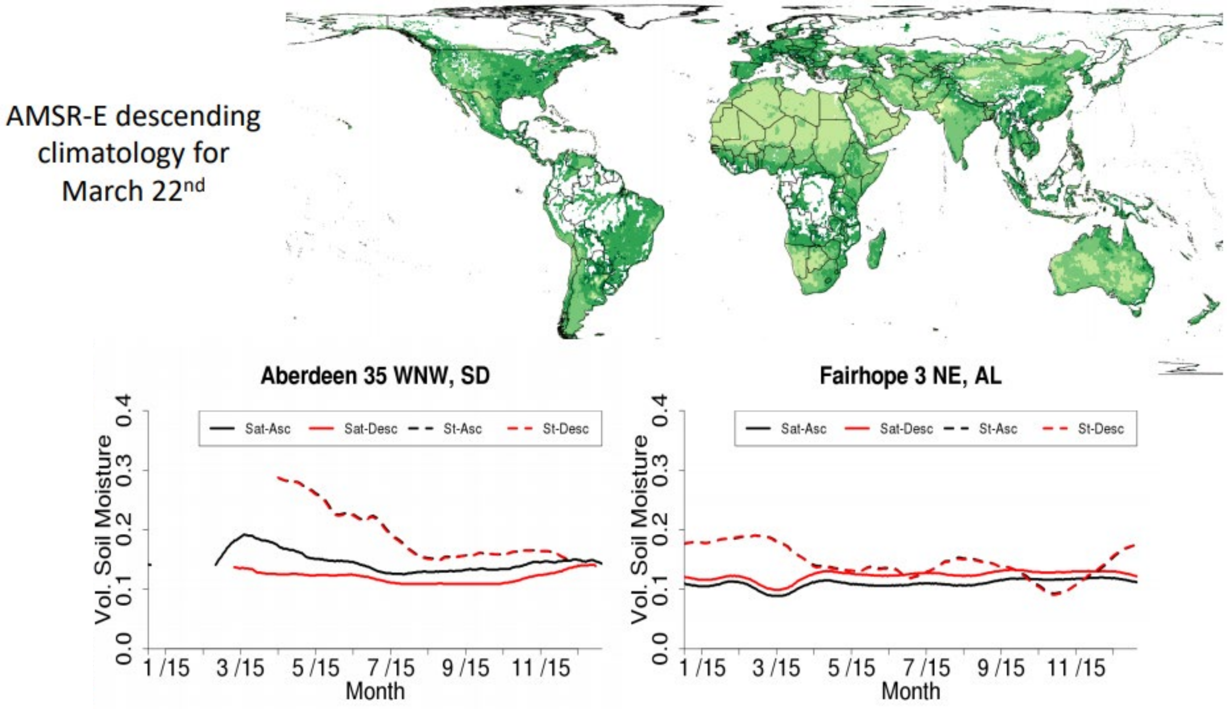


Figure 3. Standardizing satellite soil moisture observations using techniques developed by NCEI to estimate climate normals for short time series (5+ years) by sampling across the target date to surrounding dates. This approach has been used successfully to standardize relatively short time series of in situ soil moisture observations at USCRN stations. Note that the standardized soil moisture time series at each location for Ascending and Descending orbits overlap so only one dashed trace is visible.

In conclusion, substantial progress was made along all three activities in support of NIDIS during FY19, and this work will be continued in FY20 and lead to a manuscript for publication:

Leeper, R.D., B. Petersen, M.A. Palecki, and H.J. Diamond. Exploring the Use of Standardized in Situ Soil Moisture as a Drought Indicator. In preparation for the Journal of Applied Meteorology and Climatology.

USCRN Temperature Observations and Spring Green-Up in the U.S.

During Summer 2019, Ronald Leeper and his intern Maria Cesarini evaluated the relationship between USCRN soil temperature and other temperature observations to the Normalized Difference Vegetation Index (NDVI) in the area around USCRN station locations. In situ temperature variables included air temperature, surface infrared temperature, and soil temperatures at 5 cm, 10 cm, 20 cm, 50 cm, 100 cm depths. The start of the season (SOS) dates from the satellite NDVI data were associated with the dates on which temperatures crossed three thresholds, 0°C, 5°C, and 10°C. Various methods were employed to determine SOS by finding the point of peak rate of greening in an automated fashion. Preliminary results indicate the most practical and applicable temperature variable related to SOS is the 5 cm soil temperature reaching 5°C (see graph on the next page). This work continues in FY20.

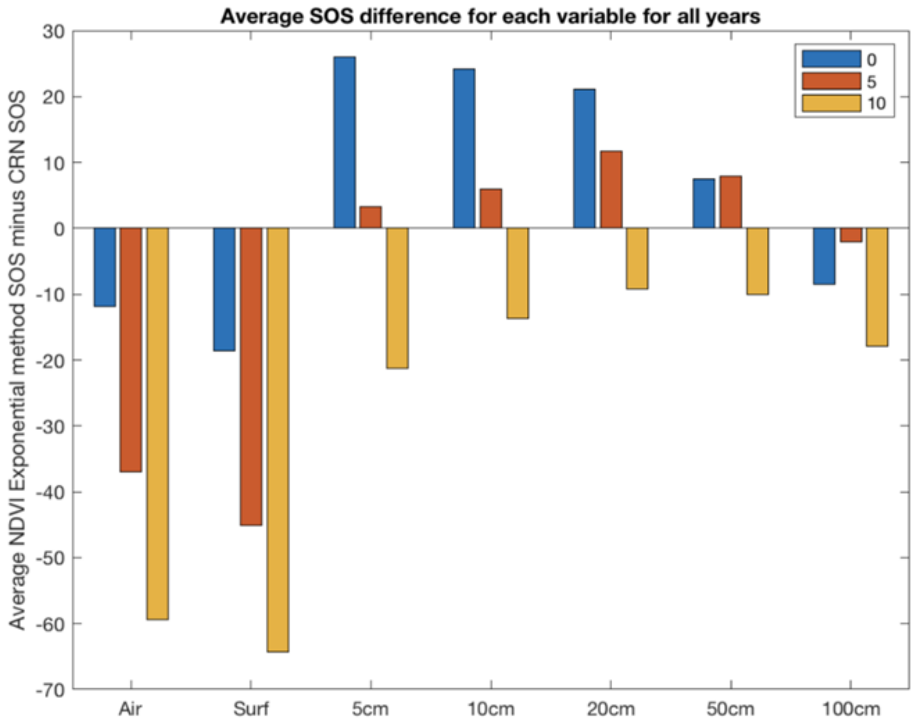


Figure 4. The lead/lag of the start-of-season in days between the temperature passing a threshold of 0°C, 5°C, and 10°C and the date of maximum rate of green-up as indicated by NDVI.

Using USCRN Precipitation Observations in Validating NOAA Hourly Precipitation Data
USCRN station precipitation observations were used in assessing the quality control of NOAA NWS Cooperative Observer Program (COOP) Network Hourly Precipitation Data (HPD). USCRN data were applied in three ways: mapping counts of precipitation events of certain thresholds; totaling precipitation on days with more than 25 mm of precipitation; and the occurrence of calculated hourly precipitation on days when associated daily precipitation measurements were dry for three consecutive days. This latter test indicated some issues with the HPD data displaying false precipitation due to gauge noise associated with solar heating of the bucket (next page). A manuscript was submitted for this work, and the HPD dataset is now available for use.

Lawrimore, J., D. Wuertz, A. Wilson, S. Stevens, M. Menne, B. Koreniewski**, M.A. Palecki, R.D. Leeper**, T. Trunk. Quality Control and Processing of Cooperative Observer Program Hourly Precipitation Data. Submitted to Journal of Hydrometeorology.

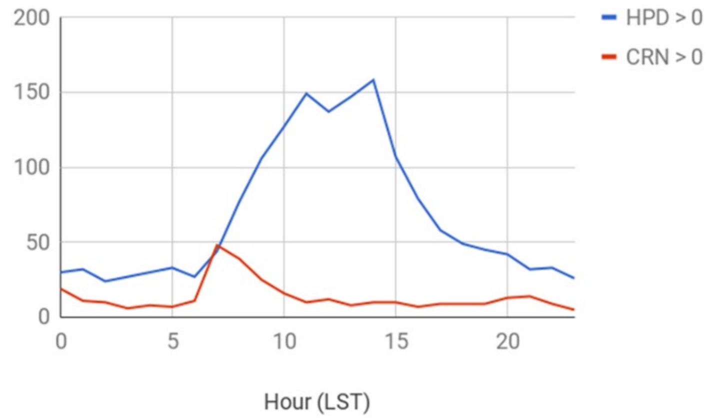


Figure 5. Diurnal distribution of the 1872 hours with precipitation in the C-HPD (blue) and 578 USCRN hours (red) on days otherwise identified as dry using COOP/GHCNd data.

As an outcome of this project, we now have an independent data set to which to compare USCRN extreme precipitation exceedance counts. While it has been observed by a previous Hollings Scholar, Emma Scott, that USCRN stations observe considerably more 1-yr, 2-yr, and 5-yr extreme precipitation events at less than daily time intervals than would be expected from NOAA Atlas 14, it was not possible to determine if these changes were due to USCRN station precipitation gauge efficiency, station density issues, or climate change. These issues will be addressed by comparing HPD and USCRN extreme precipitation statistics during FY20, leading to a manuscript submission:

Scott, E., R.D. Leeper, M.A. Palecki, and H.J. Diamond. Extreme Precipitation Event Frequency Observed by Two United States Observing Networks. In preparation for the Journal of Applied Meteorology and Climatology.

USCRN Observations and Heat Health Issues

During FY19, USCRN heat health work consisted of two major efforts by Jared Rennie and Michael Palecki: the construction of useful station-based heat indices, and the integration of heat indices with an understanding of the heat health vulnerabilities of populations. The latter effort featured the work of Hollings Scholar Mahima Kumara during Summer 2019. It has long been of interest to take advantage of the quality observations at USCRN stations to better understand heat waves and the integrated impacts of heat and humidity on human health. During FY19 there was finally an opportunity to develop further this area of USCRN activities.

Heat Indices

In previous years, much of this work was oriented toward the use of air temperature and the simple NWS heat index as the primary foci for heat health studies. However, it has become clear that to link to other work in the field, more complex measures of heat impacts on humans are required. Therefore, Jared Rennie expanded our analysis to include apparent temperature and wet bulb globe temperature. While apparent temperature (T_a) includes the impacts of wind with air temperature and humidity in the environmental impacts on human comfort, the wet bulb globe temperature (WBGT) also adds solar radiation impacts on human comfort, in addition to temperature, humidity, and wind. The latter measure utilizes a measurement of solar radiation effects as measured by a black globe thermometer, an unusual device that houses a thermistor in a small flat back globe that allows the full impact of solar radiation to be recorded. The WBGT is used extensively by groups monitoring outdoor physical activity, such as military exercises and athletic training.

While T_a can be calculated directly from USCRN observations, these stations do not have a black globe thermometer, so WBGT must be estimated. The relevant estimation equations are complex and still require variables not measured by USCRN, but that can be derived from reanalysis model output at our station locations. The accuracy of these approaches was tested by using observations from the North Carolina Econet, which has stations equipped with black globe thermometers close by two USCRN stations in Asheville and Durham NC. The results indicate a clear choice of black globe temperature estimation method (referred to as the Argonne Method below). However, it should be noted that all estimation methods have some difficulties when winds are calm.

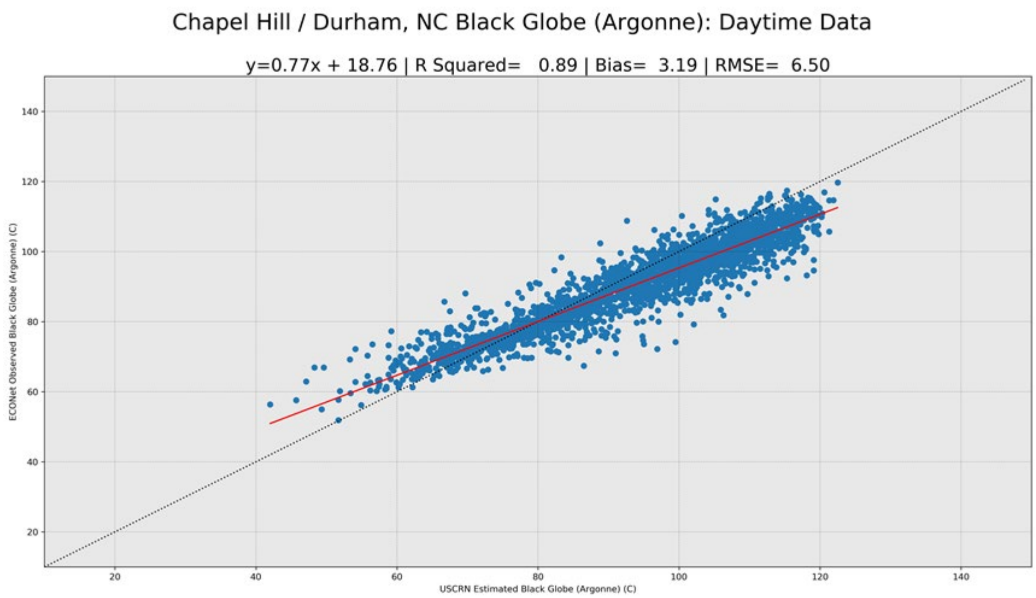


Figure 6. Measured black globe temperature from the Econet station at Chapel Hill, NC, compared to estimated black globe temperature from the USCRN station at Durham, NC, about 6 km south.
Further examinations of these estimates are planned for FY20, and a heat health alpha product will be prepared. The development process is being documented in a manuscript:

Rennie, J.J., M.A. Palecki, S. Heuser, and H.J. Diamond. Developing and Validating Heat Exposure Products Using the US Climate Reference Network. In preparation for submission to the Journal of Atmospheric and Oceanic Technology.

Heat Vulnerability

The impact of heat on human health is substantial and regularly causes morbidity and mortality every year. However, it is not only a function of the physical environment, but also the vulnerability of people to these effects. Mahima Kumara used an approach based on the literature of vulnerability and certain health indicators to create a new heat-specific vulnerability index based on variables in the table below:

Component	Variables	Variance Explained
Socioeconomic	% Poverty, % No High School Diploma, % Unemployed	23.1%
Living Conditions	% Homes built before 1980, % Population over 65 Living Alone	19.5%
Health	Obesity Prevalence, Diabetes Prevalence	18.0%
Age/Disability	% over 65 Years Old, % With a Disability	15.3%

This vulnerability index can be calculated for each county in the U.S. Southeast based on a combination of the principal component scores:

Standardized Scores	Component Index
Score ≥ 2 SD below mean	1
Score 1-2 SD below mean	2
Score within 1 SD below mean	3
Score within 1 SD above mean	4
Scores 1-2 SD above mean	5
Score ≥ 2 SD above mean	6

The pattern of heat vulnerability in the Southeast (below) is an interesting amalgam of impacts. Interestingly, relatively wealthy areas such as counties near Atlanta, Charlotte, and Raleigh have considerably less vulnerability due to modern infrastructure and young and healthy populations. However, calculations at a county level miss pockets within these areas that are much worse off in terms of economics and health. Also, urban heat islands also bring more heat to these urban areas than to surrounding areas, and these higher temperatures are often not well represented in station climatologies. More work is needed to account for these factors, and will be pursued in FY20.

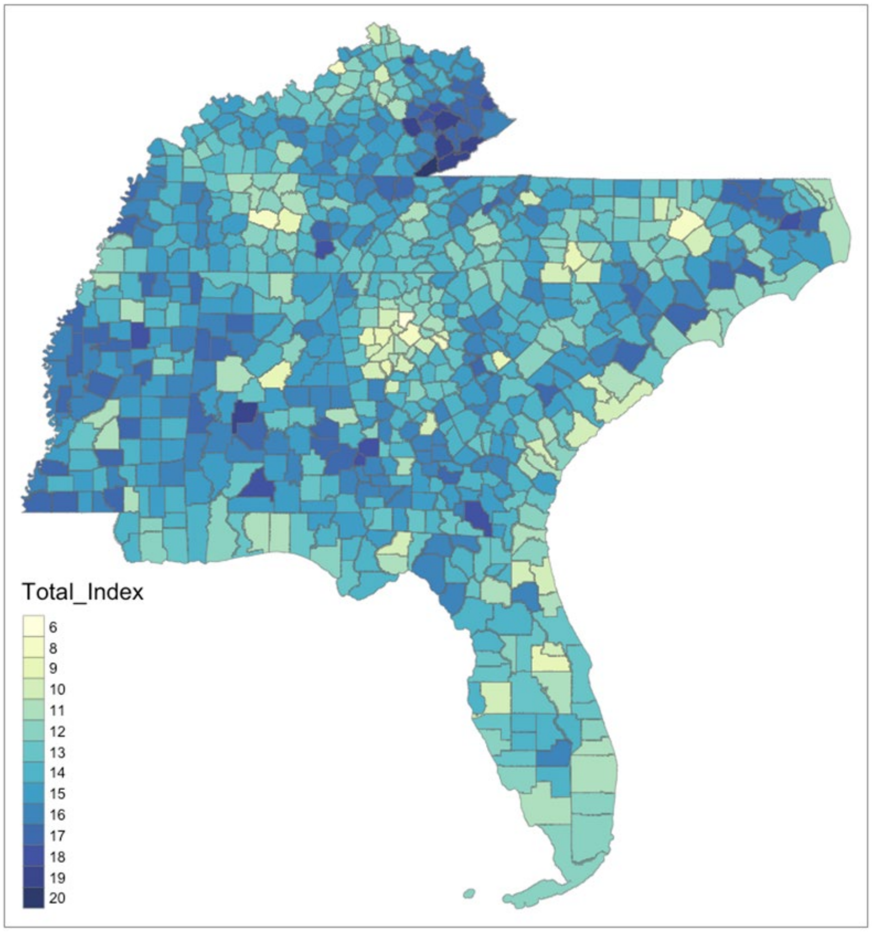


Figure 7. One way to introduce a heat-related aspect to the vulnerability index is to show how the current temperature relates to a key threshold temperature indicating human health impacts are likely. This threshold can be identified by examining how heat hospitalizations in the coastal region of North Carolina east of Raleigh related to daily maximum temperature. The graph shows a strong increase in hospitalizations on days with maximum air temperatures above 32°C (next page). This area has compound factors affecting heat vulnerability, including older housing stock with inadequate air conditioning or insulation, poverty, age and illnesses that make residents more vulnerable to heat. There are also many people working outdoors in agriculture and forestry jobs.

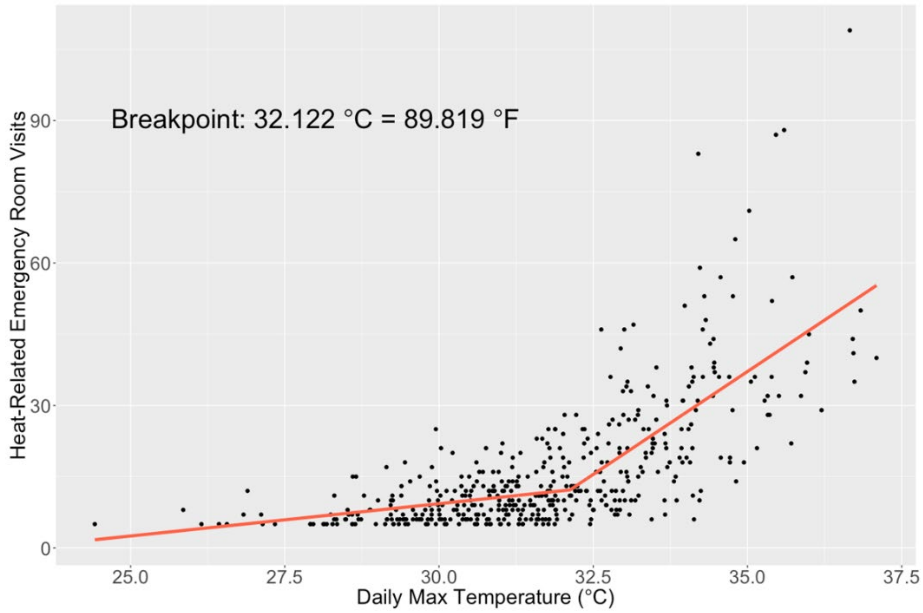


Figure 8. Heat-related hospitalizations vs. Daily Max Temperature in the North Carolina Coastal Region.

As an example of a potential approach, the heat vulnerability index (HVI) developed from census and health data mentioned above is modified for a given warm day by multiplying it with the ratio of the county maximum temperature and the threshold (32°C) temperature. These temperature data are county-based average maximums from all available NOAA climate stations. It is clear that the vulnerable areas are just inland from the relatively wealthy and ocean cooled counties directly on the coast. Interestingly, the white county is Wake County, the location of Raleigh, which is less vulnerable on a per capita basis due to its relative wealth, modern housing stock, and healthy people. A heat island effect would tend to make conditions more severe for outdoor workers and homeless individuals.

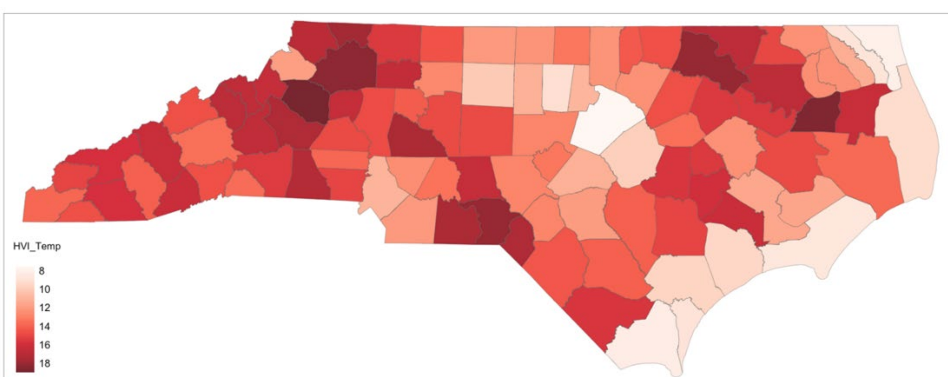


Figure 9. Map of HVI*Maximum Temperature/Threshold Temperature for July 1, 2012 in North Carolina.

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.

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 that 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 was issued in FY19. The Technical Memorandum serves as 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

[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.

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. A peer reviewed paper has been developed for submission to the Vadose journal, and we expect that paper to be submitted and published sometime in FY2020.

Development of Gridded Soil Moisture Products over the Conterminous US

This activity falls under the project known as the Soil Water and Moisture Product (SWAMP). To address a need for an enhanced utilization of the 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 113 conterminous USCRN stations with soil sensors 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.

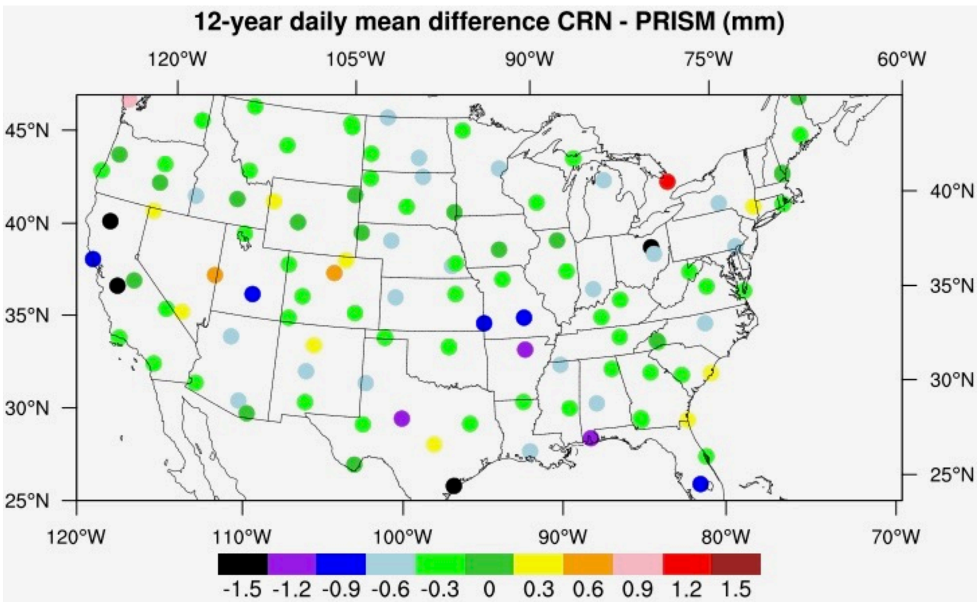


Figure 10. Mean daily precipitation difference between the USCRN and PRISM datasets between 2006 and 2018.

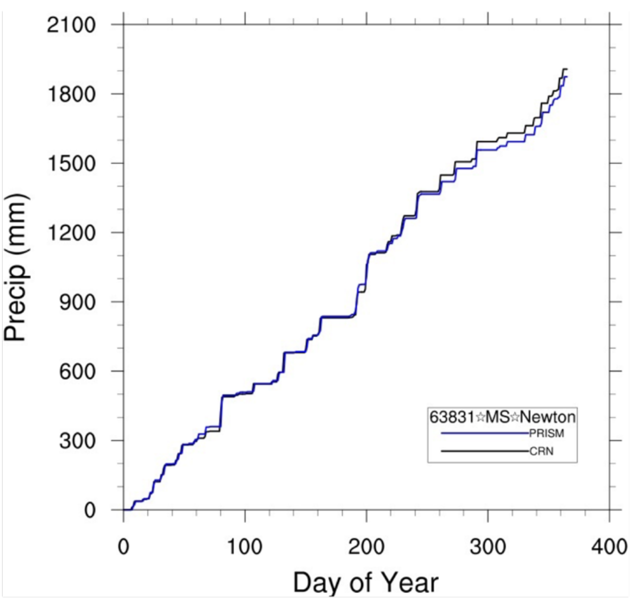


Figure 11. Comparison of running daily accumulated precipitation between the CRN and PRISM

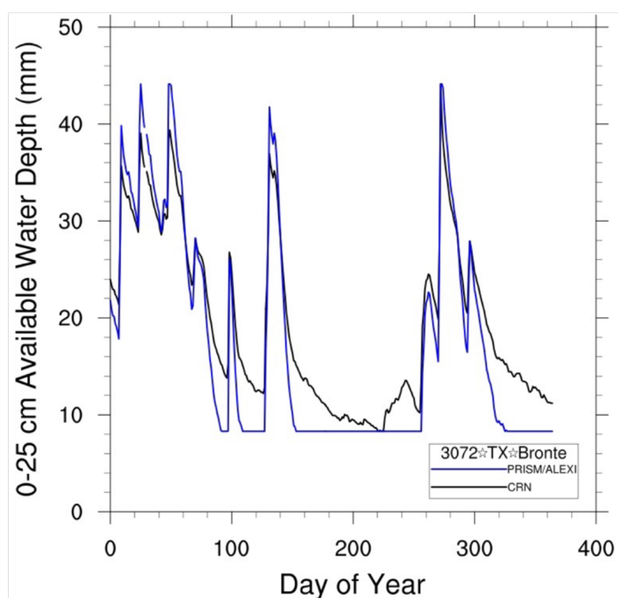


Figure 12. Measured soil moisture from the CRN compared to input/output from PRISM/ALEXI

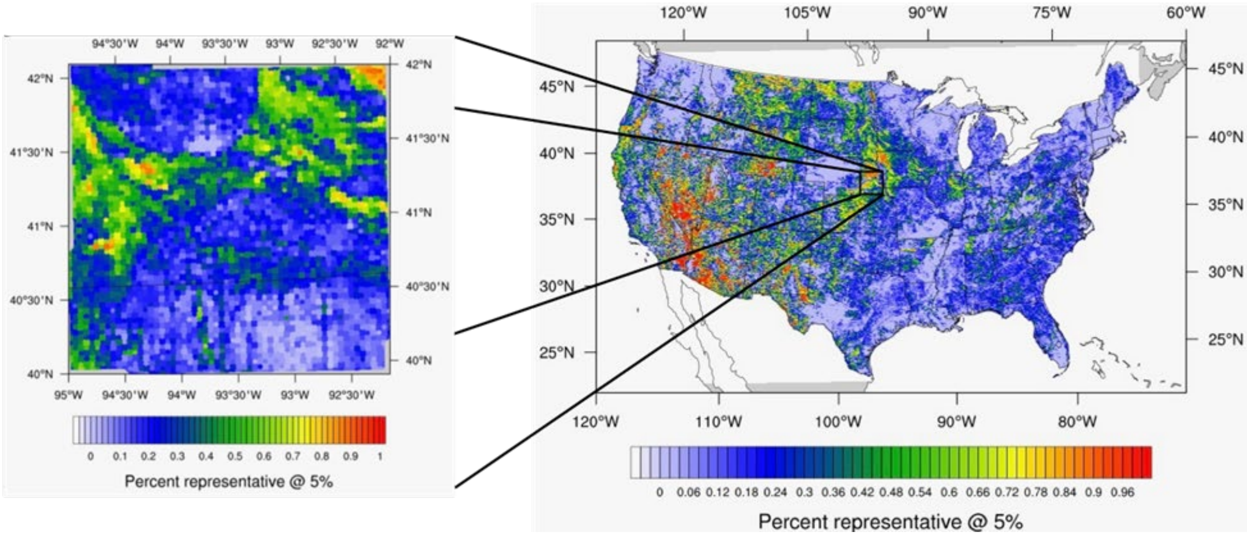


Figure 13. Percent representativeness of soil type within 5% at each soil sand, silt, and clay, in addition to matching one of the 16 vegetation classifications.

The objectives of SWAMP are to:

- Verify the robustness of the Parameter-elevation Relationships on Independent Slopes Model (PRISM) for precipitation using the US Climate Reference Network (USCRN) observations.
- Use USCRN soil and vegetation properties to match and categorize high-resolution gridded datasets of these properties.
- Develop a technique to use USCRN stations as "anchor points" to characterize soil moisture conditions as a function of soil properties and atmospheric conditions to apply to the higher-resolution datasets.

Low Porosity Double Fence (LPDF) Testing

In late 2018, a new windshield was designed as a potential replacement for the SDFIR. This new design was based on recent research that demonstrates that by lowering the porosity of a wind shield, and increasing the amount of surface area that is blocking the wind, smaller wind shields can be just as effective as larger, more porous shields (e.g. Kochendorfer et al. 2018).

The new LPDF is 4.9 m in diameter, it is only 25% porous, as opposed to the 50% porosity of both the DFIR and the SDFIR, and it is constructed out of more durable materials than the SDFIR. The Double Fence Intercomparison Reference used in the WMO Solid Precipitation Intercomparison Experiment (WMO-SPICE) is 12m in diameter (Nitu et al. 2018). The smaller SDFIR used in the USCRN is 7.9 m in diameter. And because the SDFIR is constructed out of wood, it requires periodic maintenance and eventual replacement.

In the fall of 2018, the new shield was installed at the Marshall testbed in Colorado and at the Boulder USCRN site. Both of these sites already had SDFIRs in operation. During Summer 2019 an additional LPDF was installed at the Chatham, MI USCRN site (Figure 14), where there was also a

SDFIR already in operation. The two UCSRN sites were selected because they are among the windiest and snowiest sites in the entire USCRN, and therefore are ideal for the testing of a windshield designed to minimize the effects of wind on snowfall measurements.

Testing of the LPDF will continue, but preliminary results from the winter of 2018-2019 and the beginning of the winter of 2019 demonstrate that the new shield is just as effective as the SDFIR in most conditions (Figures 15 and 16).

Figure 14. The LPDF (right side of the photo) installed at Chatham, MI.

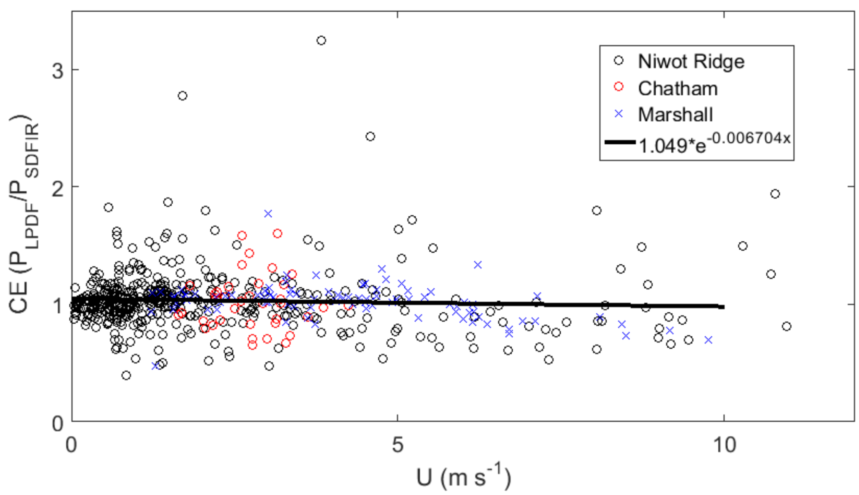


Figure 15. The catch efficiency (*CE*) of solid (T_{air} < -2 °C) precipitation from all three LPDF test sites, where *CE* is the ratio of 1h LPDF precipitation (P_{LPDF}) divided by the simultaneously measured 1 h SDFIR precipitation (P_{SDFIR}).

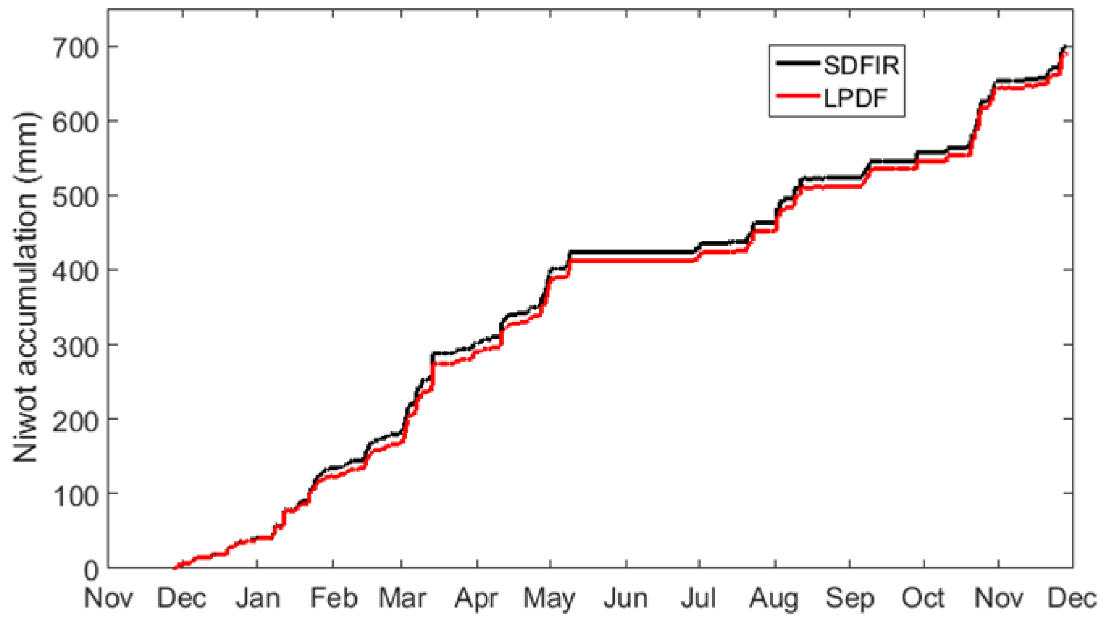


Figure 16. Comparison of Catch Efficiency of SDFIR to LPDF Fencing over the period from Nov 2018 to Dec 2019

Climate Monitoring Highlights

Record rainfall at Fallbrook 5NE, CA. A strong Pacific storm moved through the Southern California area on February 13-14, 2019. It brought 141.0 mm (5.55") of rain to the site which was not only a new record for the month, but also for any month. The previous record was 111.8 mm (4.40") set on December 21-22, 2010. When referenced to the NOAA-14 Atlas, the Point Precipitation Estimate for 141.0 mm (5.55") is 1 in 25 years. The February 2019 monthly total was 242.4 mm (9.54") which was a new record for the month. The previous record was 113.5 mm (4.47") set in February 2017. The 242.4 mm (9.54") value is also the 2nd highest total for any month. The current highest total for the station is 311.9 mm (12.28") set in December 2010 (see Figures 17 and 18 below).

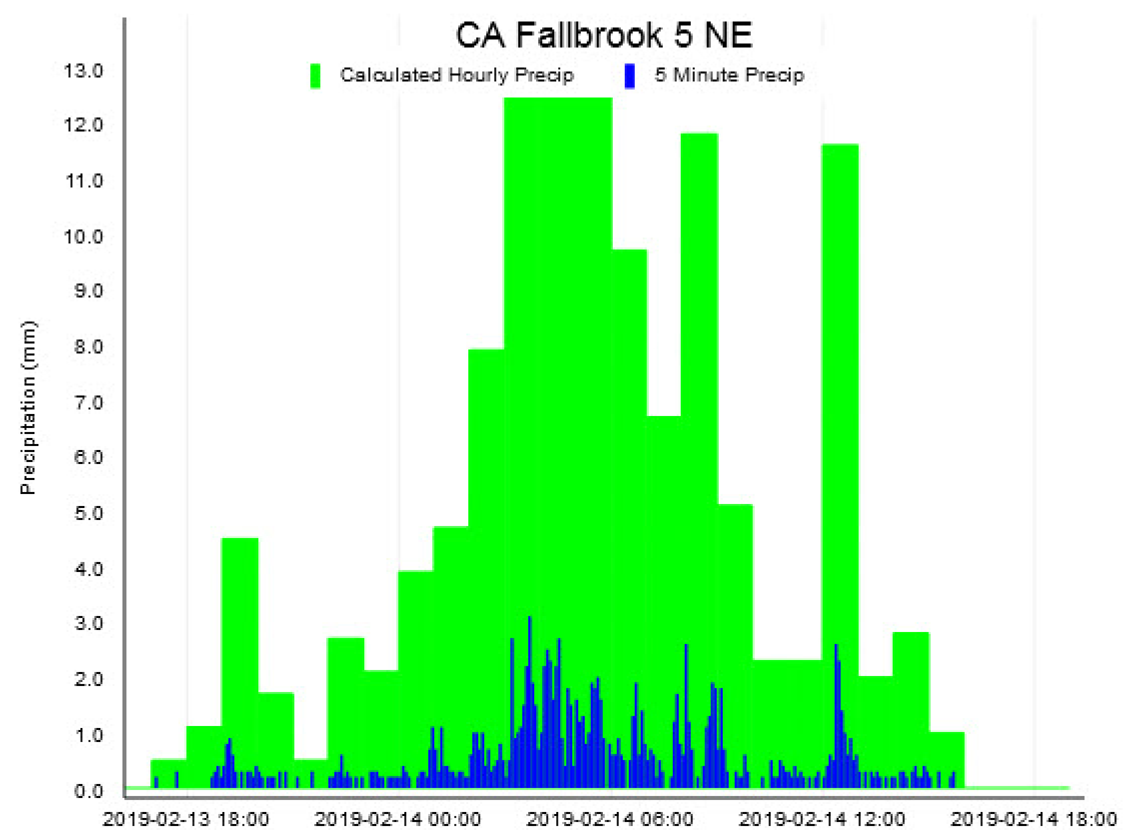
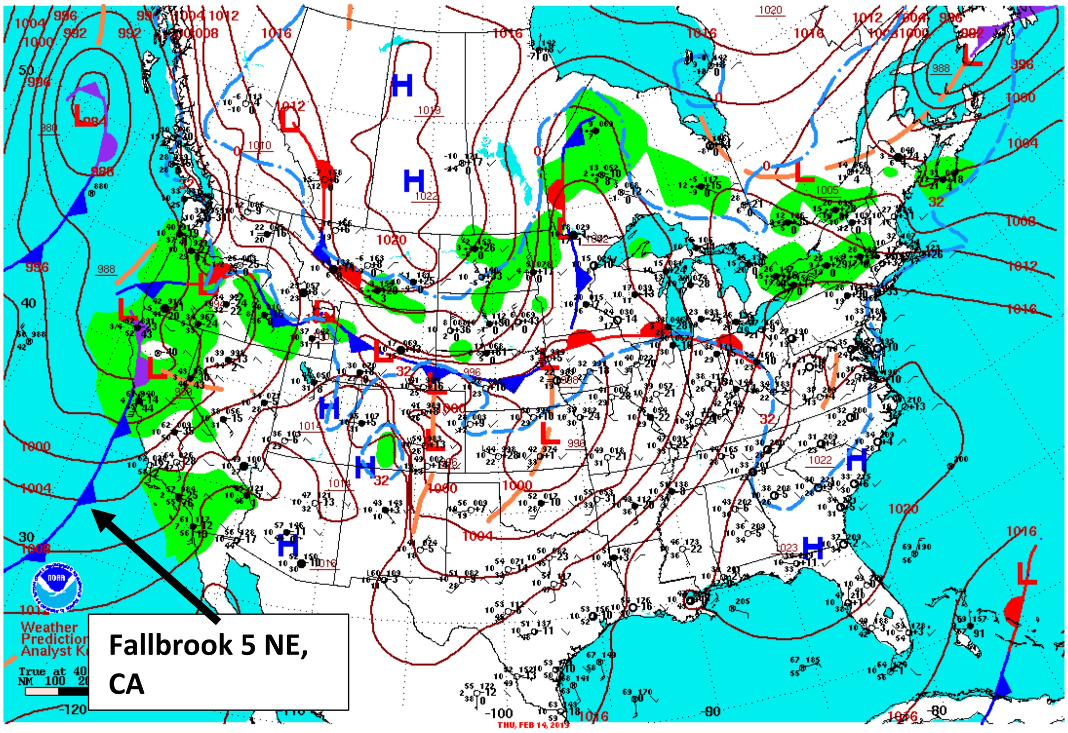


Figure 17. Calculated Hourly (green bars) and 5-minute (blue bars) precipitation amounts (mm) during record event.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 18. Daily Weather Map valid 07 EST February 14, 2019.

Record rains in North Central Oklahoma afternoon of May 20th and morning of the 21st.
Low pressure developed over the Texas Panhandle late afternoon of May 20 bringing a period of showers and thunderstorms over the USCRN sites at Stillwater 2 W and Stillwater 5 WNW. Given that the two sites are only 3 miles apart, the recorded amounts were very similar. Therefore, data for only one site (Stillwater 5 WNW) are reported. The accumulated 24-hour rainfall for the period between 0900 CST of the 20th through to 0900 CST of the 21st was 185.7 mm (7.31") which was a new station record. The previous 24-hour record was 148.8 mm (5.86") on June 1 2007.

Several days later new storms moved over the same area and brought another 85-100 mm (3.35-3.94") which produced a new seven-day record total of 288.5 mm (11.36"). There was additional significant rainfall during the month of May 2019 which brought the monthly total to 442.2 mm (17.41"). This was a new May record easily superseding the previous record of 291.6 mm (11.48") set in 2007. The May 2019 total of 442.2 mm (17.41") was only 6.3 mm (0.25") from breaking the station record for any month set in June 2007.

From a greater time perspective of the three above record amounts (e.g., 24-hour, 7 day, and 30-day periods) NOAA Atlas-14 rates the Point Precipitation Frequency for each at once in 50 years. (See Figures 19 and 20 below).

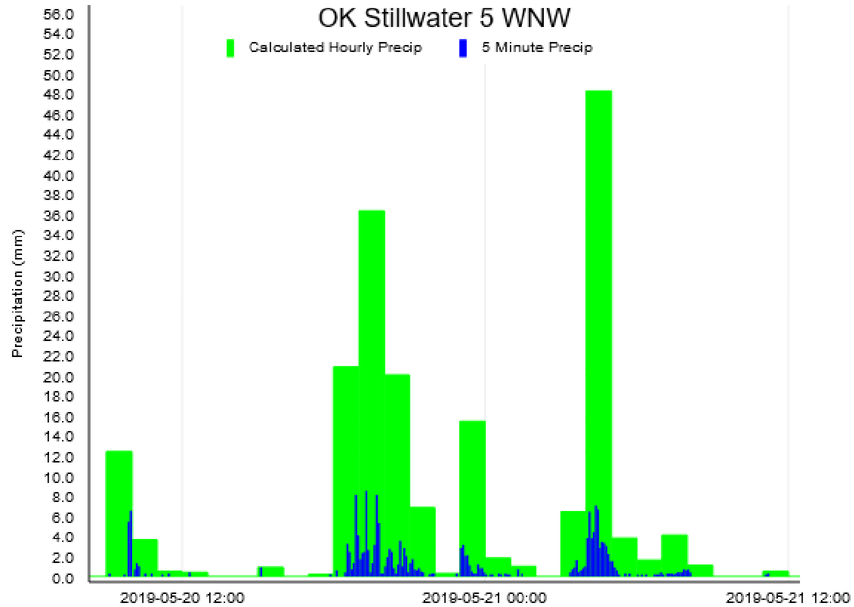
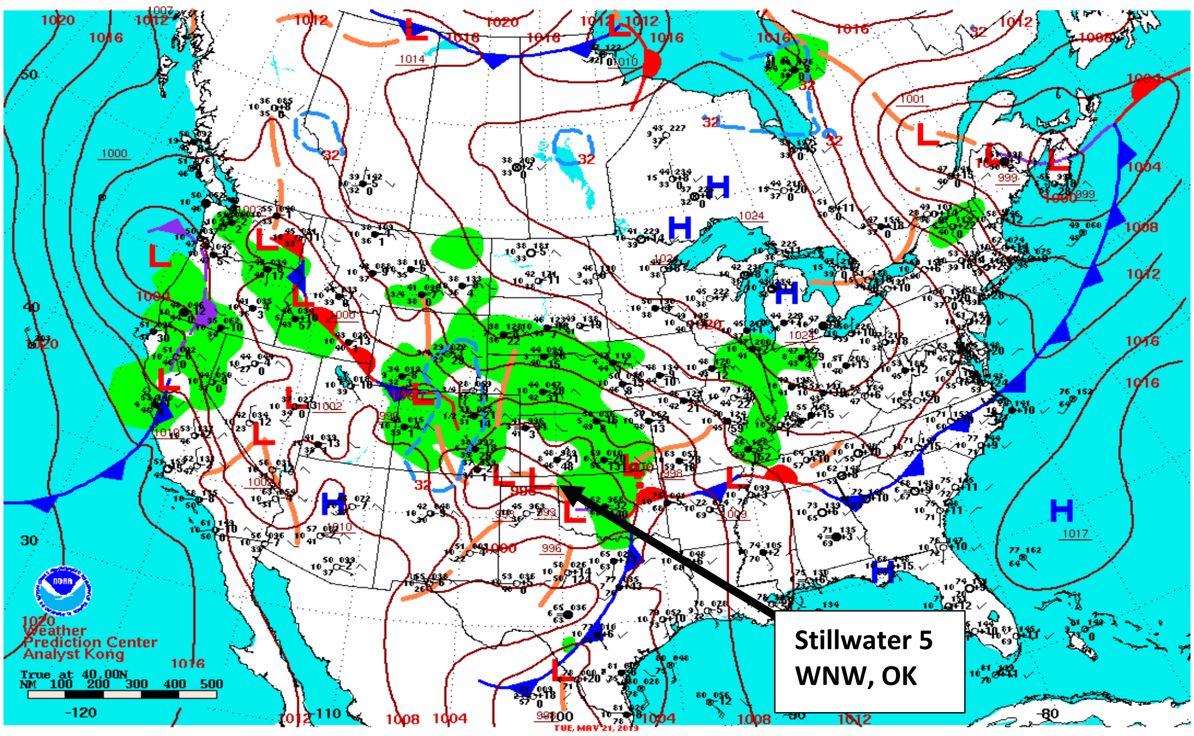


Figure 19. Calculated hourly (green bars) and five-minute (blue bars) precipitation amounts (mm) during the period of the record 24-hour event.



Surface Weather Map and Station Weather at 7:00 A.M. E.S.T.

Figure 20. Daily Weather Map valid 07 EST May 21, 2019

The Sioux Falls 14 NNE, SD site measured another record rain event for September 8-12. 2019.

Short duration intensities for periods from 5-60 minutes were not very significant. NOAA Atlas 14 rated the Point Precipitation Frequencies (PPF) for those time periods at only 5 to 10 years. However, as the event stretched into a five-day event, the PPF values became more significant ranging from 10 years for the two-day total to 100 years for four days. The NOAA 14 Atlas does not calculate values for five days, but it does calculate for seven days, and the five-day total of 8.32" was still rated at a 200-year PPF. Obviously the PPF for 5 days would place that 8.32" considerably higher.

Duration	Precipitation	NOAA Atlas 14 PPF's (No. of Years)
Minutes	mm Inches	
5	13.4 (0.53)	5
10	20.4 (0.80)	10
15	25.4 (1.00)	10
30	28.9 (1.14)	2
60	47.2 (1.86)	5
Hours		
24	79.5 (3.13)	5
Days		
2	104.6 (4.12)	10
3	152.1 (5.99)	50
4	177.8 (7.00)	100
5	211.3 (8.56)	200*

*7-day PPF estimate.

Large September snowfall over and east of Glacier National Park, MT. Snowfall amounts ranged from 6 to 52 inches. Based on Glacier NPS reports, the area near our USCRN site located one- mile SSW of the St. Mary NPS Visitor Center, received about 42". The recording precipitation gauge at the St. Mary USCRN site reported 62.2 mm (2.45") for the storm. Temperatures during the storm ranged from -2ºC to -6ºC (28-22ºF) which would likely result in a snow to melt-water ratio close to 15:1. Based on the recorded melt-water of 62.2 mm (2.45") the estimated snow accumulation would be about 94 cm (37"). (See Figure 21 below) which shows that the greatest liquid equivalent of the snow fell in the first 10 hours of the 2+ day storm.

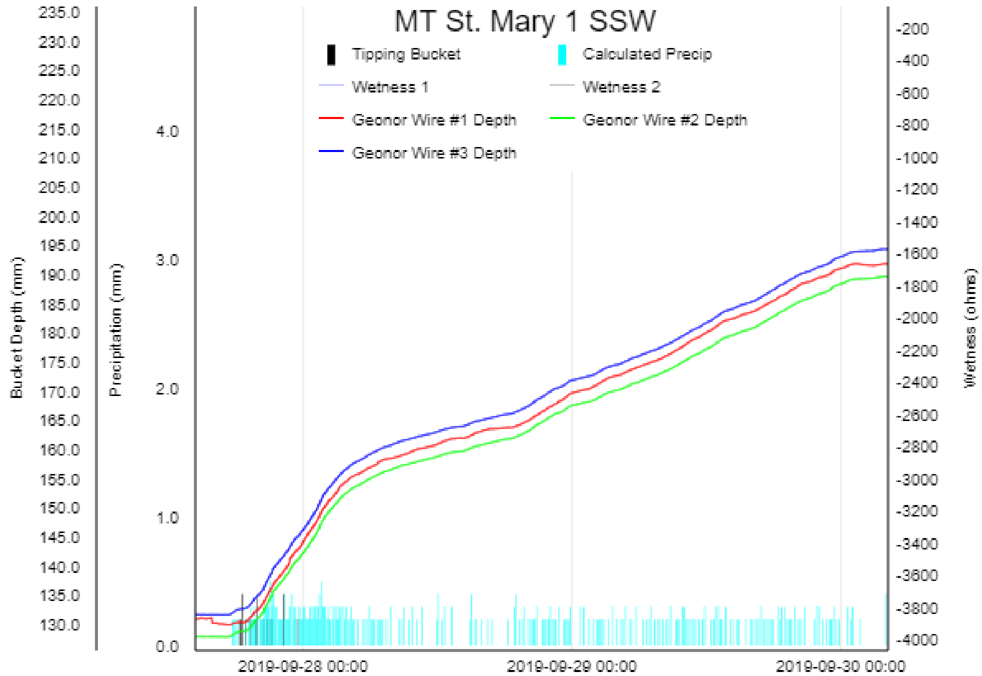


Figure 21. Accumulation graph showing each of the three sensing wires (blue, red, green) used to calculate the official 5-minute precipitation amounts indicated in light blue at the bottom of the graph.

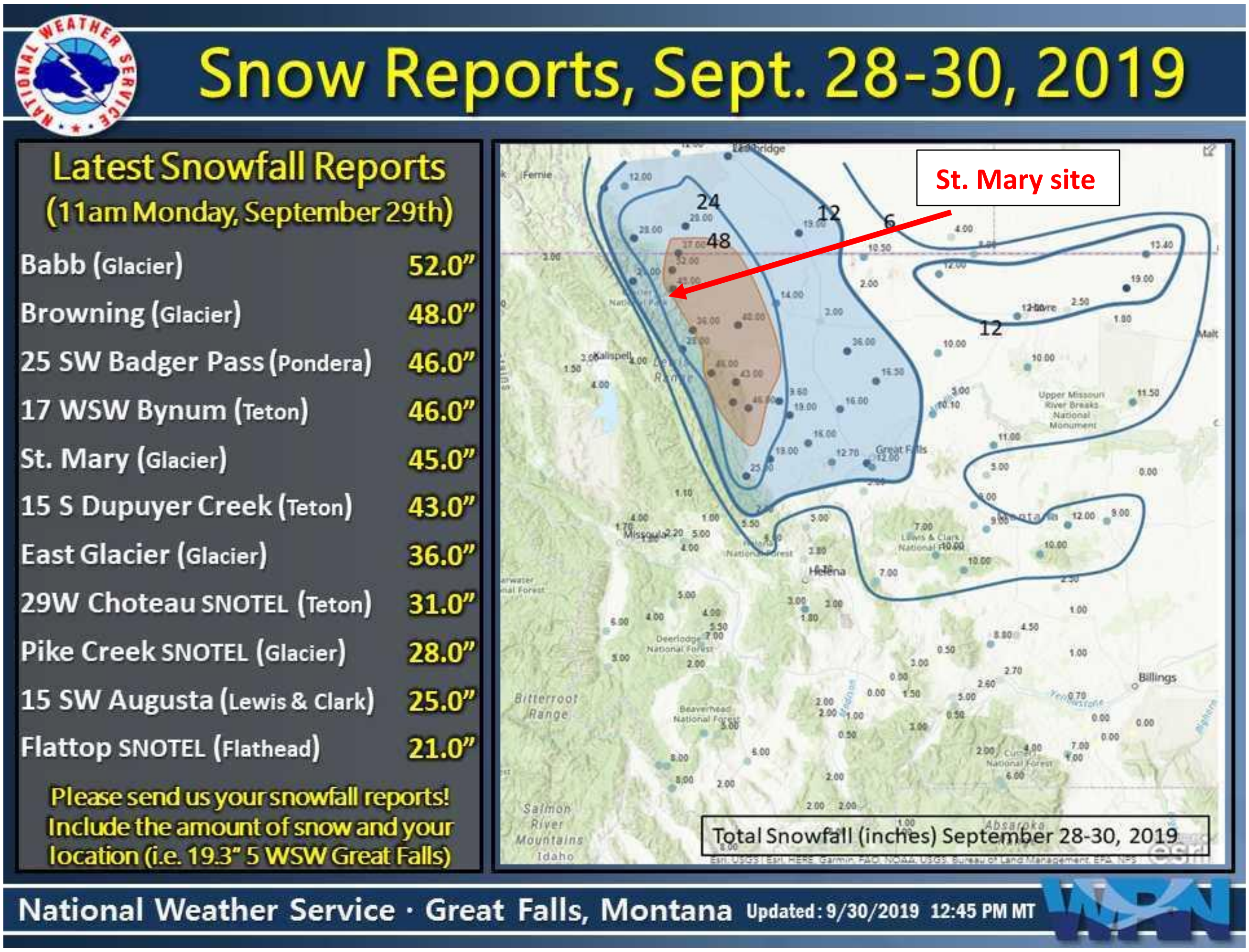


Figure 22. Spatial analysis of the snowfall totals for the storm (inches only).

Figure 23. Snow and drifted snow at St. Mary Visitor Center during the storm on Sept. 29. 2019. The USCRN site is only one-mile SSW of the Visitor Center, (Photo credit National Park Service St. Mary, MT).

USCRN Station Sets Network Record for Minimum Temperature. The US Climate Reference Network station near the town of Ruby located in central Alaska reached a minimum temperature of -49.7ºC (-57.5ºF) on 28 December 2019 (see Figure 24 for location). The temperature was observed at 2:20 AM local time and remained for the 02:25 and 02:30 observations. Two other USCRN stations in interior Alaska at Ivotuk and Toolik Lake reached minus 40ºC/F or lower that morning. While the temperature at Ruby was not the coldest reported in Alaska that day, it is the lowest temperature ever recorded by automated and fan aspirated temperature sensors operating at a USCRN site in such extreme winter conditions.

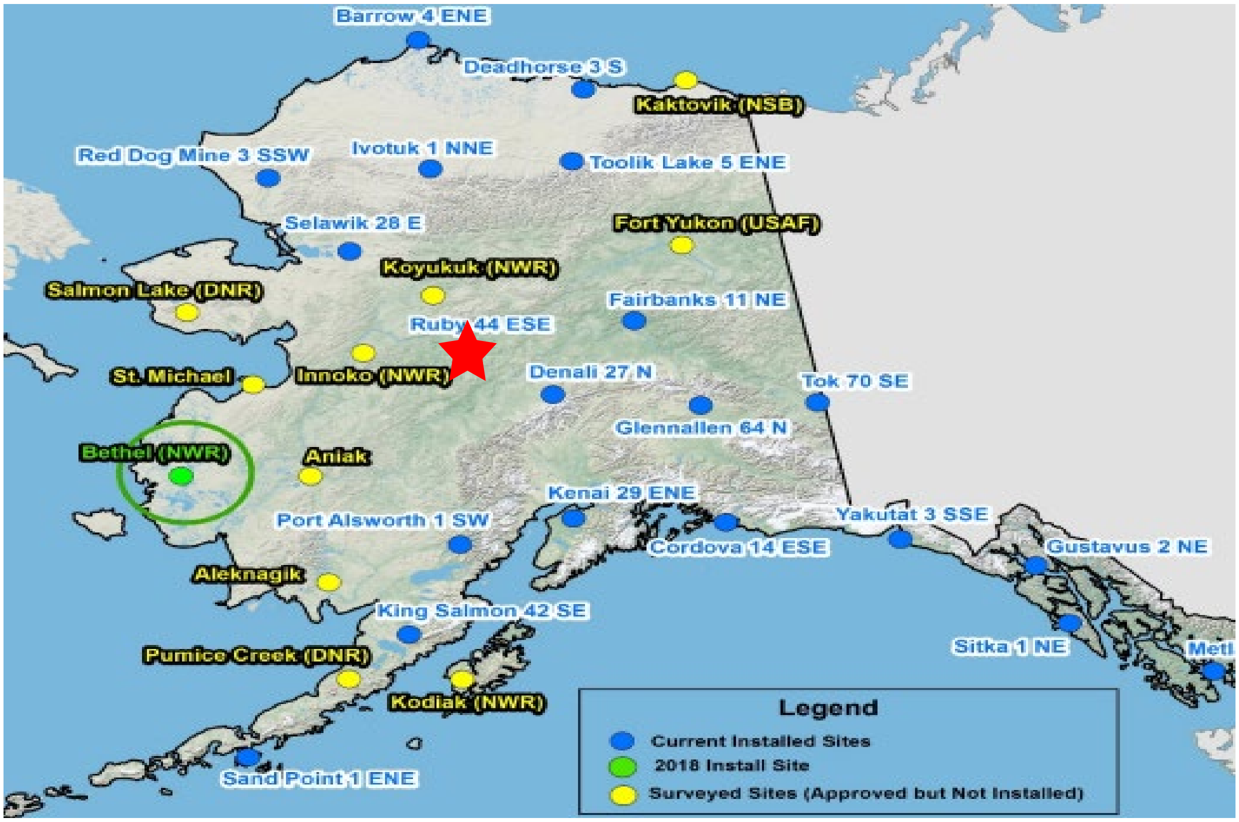


Figure 24. Map showing the location of installed sites through 2018 (blue dots) and surveyed sites for future installation (yellow dots). The Ruby site is indicated with the red star.

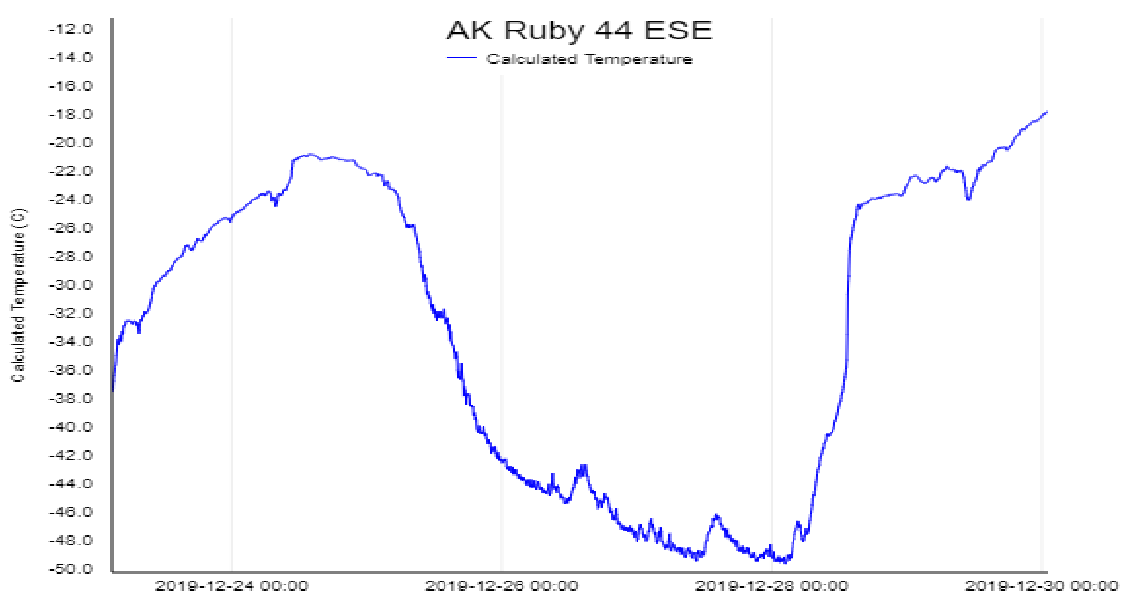


Figure 25. Autographic trace of the ambient temperatures at the Ruby 44 ESE site Dec. 24-30, 2019.

AK Ruby 44 ESE [Aug 27 2014 – Dec 31 2019]

2019-12-28 0300 Local | Go

Temperature (°C)

AIR TEMPERATURE (°C)									
LST	LDT	UTC	SENSOR #1	SENSOR #2	SENSOR #3	SECONDARY SENSOR #1	SECONDARY SENSOR #2	SECONDARY SENSOR #3	CALCULATED
02:05	02:05	11:05	-49.5	-49.4	-49.5	-49.5	-49.5	-49.5	-49.5
02:10	02:10	11:10	-49.3	-49.2	-49.2	-49.3	-49.3	-49.3	-49.2
02:15	02:15	11:15	-49.5	-49.4	-49.5	-49.5	-49.5	-49.5	-49.5
02:20	02:20	11:20	-49.7	-49.7	-49.7	-49.7	-49.7	-49.7	-49.7
02:25	02:25	11:25	-49.8	-49.7	-49.7	-49.8	-49.8	-49.8	-49.7
02:30	02:30	11:30	-49.7	-49.6	-49.7	-49.7	-49.7	-49.7	-49.7
02:35	02:35	11:35	-49.6	-49.6	-49.6	-49.6	-49.6	-49.6	-49.6
02:40	02:40	11:40	-49.6	-49.5	-49.6	-49.6	-49.6	-49.6	-49.6
02:45	02:45	11:45	-49.3	-49.2	-49.2	-49.2	-49.2	-49.2	-49.2
02:50	02:50	11:50	-49.1	-49.0	-49.1	-49.1	-49.1	-49.1	-49.1
02:55	02:55	11:55	-49.2	-49.1	-49.1	-49.1	-49.2	-49.1	-49.1
03:00	03:00	12:00	-49.3	-49.2	-49.2	-49.2	-49.2	-49.2	-49.2
Hour Average									-49.4
Hour Min (*)			-49.8	-49.7	-49.7	-49.8	-49.8	-49.8	-49.7
Hour Max (*)			-49.0	-49.0	-49.0	-49.0	-49.0	-49.0	-49.0

Figure 26. Temperature table from USCRN Web site for the 5-minute values for the hour from 02:05 through 03:00 LST. The red vertical line on the right highlights the three consecutive record observations. As can be seen there are six different sensors listed, the first three are the Primary ones used for official calculations of the 5-minute climate observations. The Secondary sensors are used only if the Primary ones become inoperative. Note that there is no more than a 0.1ºC difference amongst any of the six sensors for each of the 12 observations of the hour. This truly demonstrates the high quality of sensors used in the USCRN Network even when exposed to these extreme conditions.

Plans for FY20

A number of long-term science projects will continue or commence during FY19:

FY2020 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.

Task 1: Soil Moisture Operations and Standardized Soil Moisture Index Production
The operations to support improve soil moisture quality control and continue development of standardized soil moisture and soil climatology products continues in FY20. The beta version of the standardized soil moisture and soil climatology are available on the USCRN Web site at our quality-controlled dataset web page: https://www.ncdc.noaa.gov/crn/qcdatasets.html. Specific files for climatologies are at: https://www1.ncdc.noaa.gov/pub/data/uscrn/products/soilclim01/, and the standardized data are at: https://www1.ncdc.noaa.gov/pub/data/uscrn/products/soilanom01/. The operational software to produce the standardized hourly soil moisture data in real time has been prepared and tested, and the commencement of this production is currently waiting on NCEI archival processes that must be in place before the real time data are made available to the public.

Improvements in quality control of USCRN soil moisture data are ongoing and will continue into FY21. One of the most important of these is the beginning of a new project to apply machine learning techniques to both real time and post processing of soil moisture data. The project to integrate new Acclima soil moisture probes in the USCRN soil moisture datastream are also in progress. The fundamental monthly examination of soil moisture through manual inspection has been improved through the provision of new graphing and review statistics. The provision of quality soil moisture data to all users, including the National Soil Moisture Network, continues to be the primary USCRN soil moisture activity.

New work is planned to build on lessons learned from manual soil moisture observation quality control and develop several improved automated checks for soil probe performance problems.
Acclima soil moisture probes are transitioning to standard inclusion in the USCRN after exhaustive examination of their quality and fidelity. A new study is planned to evaluate the efficacy of using soil specific coefficients in the equation translating legacy dielectric observations to volumetric soil moisture values. Other measures to improve the homogeneity of the data during the transition from legacy Hydra to Acclima probes are under consideration. This is expected to lead to improved continuity of the soil moisture observations through this probe transition.

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

After receiving robust feedback from partners and journal article reviewers, some aspects of the standardized soil moisture indices previously developed were reconfigured and improved prior to release. A second product, USCRN Soil Moisture Climatology, will also be released at the same time. This has extended the public release date into FY20, when a standard Operational Readiness Review is scheduled and operational production will commence by the National Centers for Environmental Information (NCEI). The publication supporting this product was released in FY19.

Task 2: Development of Drought Indices Based on In Situ Soil Moisture Observations and the Application of Standardization Methods to Satellite Soil Moisture Estimates
The purpose of this product is to provide real time U.S. Climate Reference Network soil moisture guidance to U.S. Drought Monitor authors, NCEI Monitoring Section, and a number of government agencies and private entities in agriculture, water resources, and environmental sectors. A standardized soil moisture data set has been developed and is available to the public as a beta version. Work is progressing to understand the relationships between standardized soil moisture state and USDM drought status determinations in the past, especially the onset and worsening of drought conditions. Indices based on the standardized soil moisture data that are most helpful in anticipating changes in drought conditions will be in beta release by this project before the end of FY20, with a journal article submitted. The technical aspects of NCEI final approvals will extend into FY21.

- Tremendous progress was made in this activity during FY19, exploring the use of various temporal combinations of standardized soil moisture anomalies, percentiles and counts of hours exceeding threshold percentiles to characterize drought events.
- This work will continue through much of FY20, and incorporates three elements: (1) a standard definition of drought events using the USDM status at each USCRN station location; (2) a direct examination of prototype drought indices against these USDM drought events; and (3) a comparison of the most promising drought indices to other existing drought indices, such as SPI and ESI, and vegetation state as indicated by NDVI.
- Presentation of this work in preliminary form at the USDM Forum in Bowling Green, KY in September 2019 led to very useful inputs that will be incorporated into the project.
- A publication will be submitted during FY20 based on this work substantiating the utility of the final choices of operational drought indices.
- Presentation at 100th AMS Conference.

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 by the NCEI USCRN Team for in situ observations will be studied for their applicability to satellite observations.

The preliminary work on this project during FY19 revealed that AMSR-E soil moisture data sets were limited in their expression of variance in surface soil moisture, and so since this was perhaps not the best data source on which to base this project. During FY20 the standardization methods discussed in Leeper et al. 2019 will be applied to an existing satellite soil moisture compilation, such as the Soil Moisture Operational Products System (SMOPS) soil moisture dataset from NOAA NESDIS (or a SMOS/SMAP compilation if available in a timely manner) during the period overlapping the USCRN soil moisture capability. The results will be compared to USCRN standardized soil moisture values at station locations.

Task 3: Application of Standardization Methods to Satellite Soil Moisture Estimates
This applied research project is ongoing in FY20 and will continue into FY21. The work to compare in situ USCRN standardized soil moisture data to satellite soil moisture data is underway, and has been considerably accelerated by the provision of a student intern to cooperative institute affiliate Ronnie Leeper by the North Carolina Institute for Climate Studies, North Carolina State University, through a competitive process. Comparisons of volumetric soil moisture between the USCRN and the Copernicus Surface Soil Moisture Dataset have been completed, and the standardization portion of the project is underway.

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FY20 Deliverables for NIDIS
- Operational quality control of USCRN soil moisture observations and improvements of quality assurance systems; cooperation with NCSMMN activities.
- Completion of drought indices development and submission of a journal article.
- Release of operational standardized soil moisture data and drought indices.

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:

- Two new stations are planned to be deployed in Alaska during the summer 2020 building season, which will bring us closer to the eventual final total of 29 stations across Alaska.
- 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. The onset of COVID-19 in March 2020 will have implications for USCRN over all of FY20 and these will be documented in the FY2020 report for USCRN. Implications will most likely be with respect to the ability to continue to build out the USCRN in Alaska.