Geosci. Instrum. Method. Data Syst. Discuss., doi:10.5194/gi-2016-17, 2016
Manuscript under review for journal Geosci. Instrum. Method. Data Syst.
Published: 14 June 2016

Geoscientific Instrumentation Methods and Data Systems
Open Access
Discussions

The Niwot Ridge Subalpine Forest US-NR1 AmeriFlux site – Part I: Data acquisition and site record-keeping

Sean P. Burns[1,2], Gordon D. Maclean[2], Peter D. Blanken[1], Steven P. Oncley[2], Steven R. Semmer[2], and Russell K. Monson[3]

[1]Department of Geography, University of Colorado, Boulder, Colorado, USA
[2]National Center for Atmospheric Research, Boulder, Colorado, USA
[3]School of Natural Resources and the Environment, University of Arizona, Tucson, Arizona, USA

Correspondence to: Sean P. Burns (sean@ucar.edu)

Abstract. The Niwot Ridge Subalpine Forest AmeriFlux site (US-NR1) has been measuring eddy-covariance ecosystem fluxes of carbon dioxide, heat, and water vapor since 1 November, 1998. Throughout this 17-year period there have been changes to the instrumentation and improvements to the data acquisition system. Here, in Part I of this three-part series of papers, we describe the hardware and software used for data-collection and metadata documentation. We made changes to the data acquisition system that aimed to reduce the system complexity, increase redundancy, and be as independent as possible from any network outages. Changes to facilitate these improvements were: (1) switching to a PC/104-based computer running the NCAR NIDAS software that saves the high-frequency data locally and over the network, and (2) time-tagging individual 10-Hz serial data samples using network time protocol (NTP) coupled to a GPS-based clock providing a network-independent, accurate time-base. Since makings these improvements almost two years ago, the successful capture of high-rate data has been better than 99.98 %. We also provide philosophical concepts that shaped our design of the data system and are applicable to many different types of environmental data collection.

1 Introduction

One goal of the long-term measurement of eddy-covariance ecosystem fluxes is to calculate annual net cumulative transport of carbon, heat, and water vapor between the underlying surface and the atmosphere (e.g., Aubinet et al., 2012). In order to perform this task accurately, these yearly calculations require continuous data (i.e., no data gaps) which places stringent demands on the data-collection hardware and software, as well as the persons collecting the data. The collection of such high-frequency turbulence data is rife with challenges. Within the past 2-3 decades, many of these flux measurements have been made from towers placed in different ecosystems, and used to monitor the environment (Baldocchi et al., 2001). These towers are often inter-connected into regional networks such as, North and South America (AmeriFlux, Boden et al. (2013)), Europe (EuroFlux or CarboEurope), Australia (OZFlux), Asia (AsiaFlux), the National Ecological Observatory Network (NEON), and the Integrated Carbon Observation System (ICOS), to name a few.

Part I of our three-part paper describes the data acquisition system used at the Niwot Ridge Subalpine Forest AmeriFlux site (US-NR1, more information at http://ameriflux.lbl.gov), with an emphasis on how the system has evolved over time. Part

II describes the US-NR1 site characteristics and Part III describes the data quality assurance (QA/QC), gap-filling, and in-situ tests for checking long-term data quality. Overall, the underlying philosophies used to collect and process the US-NR1 data (and which Part it is related to) are:

- Whenever possible (and reasonable): collect and archive data at as high a sample rate as possible (Part I)
- For high-frequency data, time stamps of individual data samples are essential (Part I)
- Provide real-time data monitoring (Part I)
- Have a robust method for documenting and smoothly handling additions and/or removals of instrumentation at the site (Part I)
- Provide data users with an easily-accessible blog or logbook (and photos) which details activities at the site (Part I)
- Whenever possible (and reasonable): include redundant sensors and/or have QA/QC checks performed by sensor inter-comparisons (Part III)
- Make use of meteorological data from nearby measurement sites for quality-control, gap-filling and determination of sensor drift (Part III)

Early US-NR1 publications (e.g., Monson et al., 2002; Turnipseed et al., 2002) documented the primary instruments used and provided brief descriptions of the data collection. Subsequent US-NR1 publications often contained additional instrumentation details (e.g., Burns et al., 2015, their Appendix A); however, the focus of these papers has been on scientific findings, not data system details. There are many excellent references on data acquisition hardware and software with an emphasis on collecting high-frequency data (e.g., Van Atta, 1974; Aubinet et al., 2000; Billesbach et al., 2004; van der Molen et al., 2006; Matese et al., 2008; Behn et al., 2008) as well as practical advice related to data acquisition within the eddy-covariance literature (e.g., Rebmann et al., 2012; Burba, 2013) and textbook overviews of atmospheric data-collection techniques and sensors (e.g., Kaimal and Finnigan, 1994; Emeis, 2010). Most papers, however, provide only a short description or summary of the data acquisition with more detailed information found in college theses, manufacturer literature, or institutional reports. In general (and with good reason), the flux community has placed more emphasis on publishing details of flux calculations (e.g., Massman and Lee, 2002), the downstream data QA/QC (e.g., Papale et al., 2006; Göckede et al., 2008; Foken et al., 2012), or software comparisons (e.g., Mauder et al., 2008).

Data acquisition technology changes rapidly. For example, over the past decade, as data disks have become cheaper with increased capacity, storing high-rate data has become easier. Recently, small single-board computers such as the Arduino and Raspberry Pi and related open-source software have opened up the future for new ways to think about and implement data acquisition. The data acquisition papers listed above rarely discuss logistical details related to long-term measurements. Though such considerations are often fairly straightforward and logical, enactment of them early-on in the data-collection process is crucial for successful implementation of long-term (i.e., multi-decade) scale measurements. For example, having the metadata available to properly extract and process (or re-process) all of the high-frequency raw data collected since day 1 is an important consideration for any data collection and related software packages. Many modern instruments (such as the LI-COR model LI-7200, and others) now make the sensor metadata a part of the raw data files. While this is extremely useful, a typical AmeriFlux site has a multitude of complex and varied instruments that need to be kept track of, going beyond the metadata of a single sensor. In our study we provide not only the details of data-acquisition hardware and software; we also describe our experience and methodology for documenting and recording site metadata and configuration changes.

The specific goals in Part I of our study are the following: (1) describe the US-NR1 data acquisition system (hardware and software) and its evolution over time, (2) document performance characteristics of the data system, and (3) create a lasting archive (provided in the supplemental material) of the current metadata, data-acquisition software, and details of activities at the US-NR1 site.

2 Niwot Ridge subalpine forest site description

The Niwot Ridge Subalpine Forest AmeriFlux US-NR1 site is located in the Rocky Mountains of Colorado about 8 km east of the Continental Divide with a 26-m walk-up scaffolding tower as the centerpiece of the site (latitude 40° 1′ 58.349″ N, longitude 105° 32′ 49.095″ W, and elevation of 3050 m). The forest near the tower is approximately 110 years old, and primarily composed of subalpine fir (*Abies lasiocarpa* var. *bifolia*), lodgepole pine (*Pinus contorta*), and Englemann spruce (*Picea engelmannii*). Typical tree heights are between 11 to 15 m. A more detailed description of the site characteristics, forest near the tower, and a map of the area which highlights pertinent locations can be found within Part II of our three-part series (Burns et al., 2016).

3 Data acquisition system

Prior to the establishment of the US-NR1 site in 1998, a trailer was parked at the National Center for Atmospheric Research (NCAR) Earth Observing Lab (EOL), and a copy of the hardware and data acquisition system being used at the time by the Atmosphere-Surface Turbulent Exchange Research (ASTER) facility (e.g., Businger et al., 1990) was created. This trailer was subsequently moved to the University of Colorado (CU) Mountain Research Station property near the Long Term Ecological Research (LTER) Mountain Climate Program C-1 site located about 500 m northeast of the US-NR1 tower. The trailer housed the tower base station computer and was connected to the tower by a four-strand fiber optic cable. As shown in Table 1, the US-NR1 hardware and software have been periodically updated to keep up with hardware and software upgrades by the NCAR EOL Integrated Surface Flux System (ISFS) group (UCAR/NCAR–Earth Observing Laboratory, 1990-present). A schematic of the data flow from instruments to final data archival on the CU campus server (urquell) as it existed between June 2004 and October 2014 is shown in Fig. 1 and the data flow after October 2014 is in Fig. 2. Each night, the raw data files were copied from a computer at the site to urquell with `rsync`. Throughout our discussion, standard unix commands will be shown in the typewriter font and we will refer to the computers within the data system by the network names which are listed in bold in

Table 1 and shown in Figs. 1 and 2. The EOL data-acquisition software described below was written in C/C++ and we have included examples of different versions of the software within the supplemental material of this paper.

3.1 Campbell Scientific CR23X data loggers

The backbone of the data acquisition system at the US-NR1 site is a set of Campbell Scientific CR23X data loggers (Campbell Scientific, Inc., 2006). The CR23X has 12 analog differential input channels (using a 15-bit analog-to-digital converter), ingests serial data from multiple instruments (typically using the Campbell Scientific Synchronous Device for Measurements (SDM) protocol), and provides control ports for sending simple commands that can be used for tasks such as opening/closing solenoid valves. The CR23Xs act as the primary interface between the instruments and the tower data system (Figs. 1 and 2). After sampling data from multiple instruments, each CR23X streams serial data to a computer at the tower (duck, quacker, or isffa) whose purpose is to time-tag the individual serial data samples as they are ingested into the high-rate data acquisition system (Sect. 3.2). For the data system to successfully sample data at a rate of 10-Hz, it was necessary to output binary data from the CR23X CS I/O DE-9 port using a pair of short-haul modems (for example, Black Box Inc., model ME800A) for RS-422 serial data streaming from the CR23X to the tower computer. For 1-Hz data sampling and streaming, the short-haul modems were unnecessary and the CR23X data output could be in ASCII using the CR23X optically-isolated RS-232 DE-9 port and a standard serial cable. For all CR23Xs, communication between the CR23X and data system occurred at a baud rate of 9600 bps.

For some instruments, such as the Applied Technologies Inc. (ATI) sonic anemometers, serial data were streamed directly from the instrument into the data system, without using a CR23X. The data system could also directly collect serial data output by the Campbell Scientific model CSAT3 sonic anemometers; however, for our purposes, the CSAT3 data were typically collected using a CR23X and the SDM protocol. This allowed the CSAT3 wind data to be synced with any measured scalar, and also conserved usage of the data system DE-9 input serial channels (which were often a limited resource).

In addition to streaming high-rate data, the CR23X data loggers were programmed to store 5-min (or 30-min prior to May 2003) averages of the measurements on the CR23X 4 Mb internal flash storage. These data were manually downloaded during site visits. Even though the CR23X internal clock can drift with time (discussed more in Sect. 3.4), saving the mean values locally was an important feature of the data system because it allowed for the collection of key meteorological variables (such as radiation, temperature and wind speed) during periods when the data system was not working. These mean meteorological variables could subsequently be used for gap-filling the turbulent flux measurements (e.g., Papale, 2012). A list of the CR23X data loggers used at US-NR1 is in Table 2, and an archive of all versions of the logger programs are included as a zip archive in the supplemental material (USNR1_logger_code.zip). As noted in Table 2, three of the data loggers (SOIL, TC, and MRS) were not connected to the high-rate data system. The SOIL and TC CR23X loggers were mostly used to measure biomass temperature and soil properties which typically do not require high-rate or fast-response measurements. These temperatures were measured using a multiplexer specifically designed to measure thermocouple temperatures (Campbell Scientific, model AM25T). The MRS CR10 logger was used to measure vertical snow temperature profiles (e.g., Burns et al., 2013).

3.2 High-rate data collection

3.2.1 ASTER/ADAM-ATI configuration (1998–2004)

The original concept of the NCAR ASTER facility was to use multiple Automatic Data-Acquisition Modules (ADAMS) to collect data from remote locations and send it back to a base station that runs the "ASTER" software (Businger et al., 1990). For the initial deployment at the US-NR1 site, a data acquisition board from ATI with 16 serial input channels that was connected to a 486 PC running Linux (dubbed duck) was used. The typical NCAR ADAM used Motorola 68000 VME hardware (running VxWorks), so the ASTER/ADAM software was modified to be compatible with the ATI data-acquisition board and thus called the ADAM-ATI software (Table 1). A copy of the manual for the ADAM-ATI duck is included in the supplemental material (USNR1_ati_duck_manual.pdf). The base station running the ASTER software was a Sun Sparc5 workstation (russter) in the trailer at C-1.

In 2002, a Dell laptop (dubbed quacker) running Red Hat Linux (2.4.18-5) replaced the duck and the ADAM-ATI software was adapted and installed on the quacker. For this upgrade, the Sparc5 (russter) in the trailer at C-1 was unchanged. In order to acquire the serial data from the CR23Xs the quacker typically had 9 DE-9 input channels (one on the back of the laptop and 8 from an Edgeport/8 USB-to-serial converter). For periods when more than 9 DE-9 input channels were needed, a USB hub was used to connect two Edgeport/8 converters simultaneously; however this setup was subject to system lockups and less robust than using a single Edgeport/8 converter. The main task of the quacker was to time-tag the incoming serial data samples from the CR23Xs and stream these data directly to russter where the raw data files were created and archived.

3.2.2 ASTER/NDAQ configuration (2004–2014)

In spring of 2004, the Sparc5 workstation in the trailer at C-1 (russter) was starting to show signs of failure. In June of 2004 russter was replaced with a Linux-based Dell PC (russter2) and the ASTER base station software was installed on it (Table 1, Fig. 1). At this time, the ADAM software had been re-coded to run on Linux-based systems and was called the NCAR Data Acquisition system (NDAQ) software. So, when russter2 became the base station, the quacker software was upgraded from ADAM-ATI to NDAQ. Even though NDAQ was considered "transitional" software by NCAR (eventually replaced by NIDAS, as described in the next section), it was used at the US-NR1 site for over 10 years.

Two network cards were installed on russter2. One network card was for the local 10.0.0.X subnet which used a pair of fiber optic cables between C-1 and the quacker at the tower. The other network card used a long network cable running under the road at C-1 to a fiber optic converter switch that was part of the MRS network (maintained by the CU campus network services), and connected russter2 to the CU campus and the outside world.

As instruments were added or removed from the tower, all data-system configuration changes were saved within the ASTER software on the base station russter2 in different OPS directories (described in Sect. 3.7). In contrast, the NDAQ software and system configuration on the quacker was relatively static. Examples of the ASTER software on russter2 and NDAQ software on the quacker are included in the supplementary material.

3.2.3 NIDAS configuration (2014–present)

In summer of 2012, russter2 experienced a hard drive failure and was starting to show signs of other problems. After discussion with EOL, it was decided to upgrade to the current EOL hardware and software, which was a single-board Eurotech PC/104 Titan computer (http://www.eurotech.com/en/products/TITAN) running the NCAR In-Situ Data Acquisition Software (NIDAS) (Maclean and Webster, 2012). After a period of testing in the lab and at the site, on 20 October 2014 a Titan PC/104 stack (isffa) running Arcom Embedded Linux (AEL v4i5) was deployed at the tower. The Titan replaced both the quacker and many of the russter2 functions, taking over the tasks of data sample time-tagging, raw data archiving, and daily copying of the raw data files to campus (Fig. 2). However, some russter2 functions, such as cockpit (Sect. 3.6), were now run on urquell (on the CU campus). The Titan was also directly connected to a GPS receiver to provide time-keeping (and time server) capability. By having the Titan perform all of these tasks, the complexity of the system (and possibility for hardware failures) was greatly reduced.

NIDAS was designed to be used on a wide variety of platforms (such as the NCAR aircraft) and is scalable for sampling small to large numbers of instruments. When a Titan PC/104 computer is combined with NIDAS, some of the key features are: small size (the Titan footprint is 90 × 96 mm), low power consumption (maximum power usage of 1.5 Watts), adaptable to diverse network configurations and data bandwidths, capable of high-bandwidth sampling with high accuracy time-tags, support for multiple I/O buses and data acquisition expansion cards, embedded processors, and adaptable to distributed displays and processing. NIDAS has also been compiled on inexpensive, single-board Linux-based computers, such as the Raspberry Pi (https://www.raspberrypi.org/). The most recent version of the NIDAS software is maintained on github (https://github.com/ncareol/nidas/wiki).

The Titan comes with 4 RS-232 and 1 RS-422 DE-9 serial ports. We combined this with an Emerald 8P Module that provided an additional 8 DE-9 serial input channels. In total, 13 DE-9 serial ports were available for inputs from the CR23Xs and other instruments (replacing the Edgeport/8 converter). Having these extra DE-9 ports allowed us to add a new CR23X data logger (the MARK CR23X, see Table 2) to the data system in November of 2014.

From a users perspective, NIDAS differed from ASTER/NDAQ in several important ways. First, any data system configuration (OPS) changes in NIDAS are recorded in a single Extensible Markup Language (XML) file, rather than in the ASTER “config” files (specific details about the OPS files are in Sect. 3.7). Second, in addition to the high-rate data being saved locally on a USB solid state thumb drive connected to isffa (considered the primary raw data files) they are also saved in real-time on urquell as long as the network connection is working (these are considered the secondary raw data files). This redundancy allows for high-rate data to continue to be collected even if the hard drive on isffa fails or the local data archiving stops for some other reason. Similar to ASTER, it is also possible to have multiple Titans (or other computers running NIDAS) simultaneously stream data into urquell, creating a single raw data file with data from multiple remote systems.

3.3 Raw data format

The NIDAS raw data files are about 50% larger than those from ASTER/NDAQ (with ASTER high-frequency raw data collection typically on the order of 100 Mb day^{-1} compared to nearly 150 Mb day^{-1} with NIDAS). The larger NIDAS file size is due to several upgrades to the binary data format, such as an absolute time-tag, support for longer samples, and minimal alteration of the data as-read from the sensor or CR23X data logger (whereas the ASTER software converts sensor data to a binary format). For time information, the ASTER binary data used a 4-byte integer that is the number of milliseconds since 00:00 UTC of the given day. In contrast, NIDAS uses an 8-byte integer that represents the number of microseconds since 1 January 1970, 00:00 UTC. The total amount of raw data collected each year is listed in Table 3. Backups of the raw data files are done using multiple methods. In addition to keeping the raw data on the urquell RAID hard drive, copies are put on DVDs, USB external hard-drives, and finally archived by the AmeriFlux project on Lawrence Berkeley National Laboratory computers.

3.4 Time-keeping

In order to collect high-frequency data, time-keeping is an important consideration. If left alone, the clock in an individual CR23X and computer will drift with time. The CR23X factory specifications for clock drift is ±1 minute per month for -25 to $50\,^{\circ}$C which degrades to ±2 minutes per month for temperatures between -40 and $-25\,^{\circ}$C. Because the serial data samples were all time-tagged by the data system computer (duck, quacker, or isffa), the internal CR23X clock was of minor importance. To synchronize the data system computer clocks and ensure accurate time-tags, network time protocol (NTP, http://www.ntp.org/) was used. NTP has the advantage of choosing a time source from either a network-based or local time server, such as the GPS pulse-per-second (PPS) output/clock (e.g., Lombardi et al., 2001). In the NDAQ configuration, russter2 used a time-server on the CU campus to maintain an accurate clock, and it was also configured as an NTP time-server to keep the quacker clock from drifting. In 2014, the Titan was directly connected to a GPS receiver (Campbell Scientific, model GPS16X-HVS) to maintain clock accuracy (e.g., Behn et al., 2008; Refan and Valizadeh, 2012) and act as the local NTP time-server. Both russter2 and the Titan/isffa were configured as precision time protocol (PTP, i.e., IEEE 1588-2002) servers to be available for any instruments that require PTP, such as the LI-COR model LI-7200/LI-7550 infra-red gas analyzer (IRGA). It would also be possible to have isffa act as a PTP, version 2 (i.e., IEEE 1588-2008) server depending on the needs at the site.

Between October 2013 and July 2015 a Campbell Scientific CR3000 data logger and a CPEC200 system with an EC155 IRGA (Campbell Scientific, Inc., 2013) were installed on the US-NR1 tower as part of an IRGA comparison experiment (e.g., Burns et al., 2014). The CR3000 data logger was connected to a second 16X-HVS GPS for precise time-keeping and scan interval regulation. The EC155 10-Hz raw data were stored locally on the CR3000 and an analog CO_2 voltage from the EC155 was also ingested by the FAST CR23X into the tower data system. For the purposes of the current study, a comparison between the 10-Hz data archived on the CR3000 and the analog CO_2 voltage provides an opportunity to examine time-stamp differences between these two (independent) systems and a way to check the data-system time-keeping accuracy.

3.5 Variable names

Because the data system at US-NR1 is based on NCAR ISFS software, we have adopted the ISFS variable-naming nomenclature. Here, we provide a short description of the naming scheme with more details at https://www.eol.ucar.edu/content/isfs-variable-names. Briefly, slow-response sensors that are sampled at a rate of 1 Hz (or less frequently) use upper-case variable names (e.g., P, T, for slow-response barometric pressure and air temperature) while the high-frequency, turbulence measurements used for eddy-covariance are named with lower-case letters (e.g., u, v, w, and tc for three wind components and temperature from a sonic anemometer). Calculated 5-min statistics are saved in a daily netCDF file (discussed in Sect. 3.6), which have variable names such as u_u, u_v, w_w, and w_tc for the variance and covariance between the variables (higher-order statistics are also calculated). Variable names can also be further qualified by attaching a suffix to indicate the measurement location or height, such as w_tc_10m.

3.6 Real-time data monitoring

The first step in data quality control is recognition of a problem or issue with the data from a particular instrument. The ASTER and NIDAS software facilitated this important task in two ways. First, it includes real-time monitoring of all variables measured by the data system in a simple display called "cockpit" (Fig. 3). This display is possible as long as network access to the data system is available. The ability to quickly scan and observe all variables at once is a key feature. As seen in the screenshot of Fig. 3, each box in the cockpit window corresponds to a different measured variable. Another helpful feature is to leave a trace of the older data (shown in light grey) so problems are easily observed. The cockpit display evolved from a similar display documented by Oncley (1989).

The second feature is that the software produces near real-time statistics (means, variances, co-variances, third moments, etc.) of the variables. Typically, a 5-minute period is used for the statistics, and they can also be re-calculated as part of the post-processing. These statistics are saved in daily netCDF files (Unidata, 2016) that are considered part of the final data product. These 5-min statistics can be used to generate plots for examining daily trends or look for problems. For an example of daily plots generated by NIDAS for QA/QC see http://www.eol.ucar.edu/isf/projects/CHATS/isff/qcdata/. As an example of what these 5-min data files look like, a full set of the daily netCDF files for 15 November from each year is included in the supplemental material (USNR1_5minute_statistics_files.zip).

3.7 Tracking configuration changes

Any long-term measurement (that is subject to setup changes over time) needs a simple, robust method for recording the metadata and software that keeps track of these changes. This is needed, for example, as new instruments are added or old instruments are removed. The ASTER and NIDAS software are designed to keep track of configuration changes using what are called the "OPS" files. This consists of a simple text file with dates and times where configuration files for each particular setup are saved in a sub-directory based on the OPS file configuration number. For the data system at US-NR1, we are currently operating on OPS 86 which suggests that there have been 86 changes to the system configuration. There have, however, actually

Geosci. Instrum. Method. Data Syst. Discuss., doi:10.5194/gi-2016-17, 2016
Manuscript under review for journal Geosci. Instrum. Method. Data Syst.
Published: 14 June 2016

been more changes than 86 because when data was first collected configuration changes were not accurately recorded. This has led to some uncertainty and guess-work in re-extracting data from the early period of US-NR1 operation (e.g., 1998–1999).

For the ASTER software, the important files that needed to be updated for OPS configuration changes were the "config" files: archive_config, channel_config, ingest.conf, prep.config, and covar.config. These were simple ASCII files that contained all the information about which serial channels were collecting which CR23X data, the format of the incoming serial data, variable names, and which variables to calculate 5-min statistics. The OPS/config files were mirrored on urquell so that the variables could be extracted from the raw, binary data files (using the ASTER `prep` command) for subsequent data processing. A file called "ops.config" contained the information about which dates/times corresponded to which OPS configuration.

For the NIDAS software, the config files were replaced with a single XML file (niwot.xml). The OPS dates and time information are in a file called "configs.xml". On the Titan, only the portion of the niwot.xml file related to the data acquisition is required. This data acquisition information is mirrored in the niwot.xml file on urquell, along with some additional information related to the 5-min statistics and cockpit display (which are both done on urquell, not the Titan). Similar to the ASTER software, `prep` is used to extract data from the raw, binary data files.

The supplementary material includes the full archive of OPS files for the ASTER (USNR1_OPS_aster.zip) and NIDAS (USNR1_OPS_nidas.zip) software as well as more details and examples using `prep` and examples of how to load these data into MATLAB (USNR1_prep.zip).

3.8 Record keeping

Complementary methods (described below) were used for archiving metadata and keeping records of activities at the site.

3.8.1 Web calendar

A simple web-based calendar is used to summarize dates when the site is visited, include a link to photos taken, and provide any additional information. The calendar website is maintained as http://urquell.colorado.edu/calendar/ and a screenshot of the web calendar from a recent month is shown in Fig. 4. Here, one can see that different colors indicate different types of activities, short descriptions of the weather and weblinks to "Details" and photos are included for each date the site is visited. There are currently over 14,000 individual photos taken during visits to the site. The usefulness of this calendar is especially apparent when the data are being analyzed and something strange or odd is observed on a certain date. This calendar allows any interested person with web access to quickly find and examine what activities (if any) were occurring on a particular day. The full set of HTML calendar webpages are included in the supplemental material (USNR1_webcalendar.zip).

3.8.2 Field logbook

The link to "Details" in the web calendar leads to the on-line electronic site logbook, http://urquell.colorado.edu/logbook/. Our logbook is created using the unix-based Tool Command Language (Tcl/Tk) coupled with the Linux simple windowing shell (`wish`) program. A screen shot of a typical logbook entry is shown in Fig. 5. The key information provided is: who

Geosci. Instrum. Method. Data Syst. Discuss., doi:10.5194/gi-2016-17, 2016
Manuscript under review for journal Geosci. Instrum. Method. Data Syst.
Published: 14 June 2016

was at the site, why the visit occurred, the weather, any miscellaneous notes, and then a detailed summary of what was done. The amount of detail provided is at the discretion of the person writing the entry. The software allows for any individuals with accounts to add information to the logbook and generate HTML output for posting on a website. Any blogging-type of software could also be used for the logbook entries. The full logbook and logbook webpages are included in the supplemental material (USNR1_logbook.zip).

3.8.3 Digital cameras

Another useful resource that has been on the US-NR1 tower since July 2007, are automated cameras or webcams (Fig. 6). In general, these cameras have been part of the University of New Hampshire PhenoCam project (http://phenocam.sr.unh.edu/webcam/) and can be used to track changes in the forest phenology (e.g., Keenan et al., 2014). The cameras that are part of the PhenoCam network all use NTP for an accurate time/date stamp on each photo. The photos also serve as an image-based way to document conditions at the site; for example, they could be used to evaluate the presence of snow on the canopy. If pointed toward the sky, these cameras can be used to help document clouds and cloud motions (e.g., Schween et al., 2007; Illingworth et al., 2007).

In mid-2014 we explored using inexpensive (≈ $100 USD) stand-alone cameras (Wingscapes, http://www.wingscapes.com/) to take photos of the clouds (Fig. 6e), track snowmelt in spring (Fig. 6f), observe liquid water evaporation/infiltration in the summer, and monitor the comings-and-goings of human activity at the site. For the Wingscapes cameras, the date/time is reset when the photos are downloaded. We have had mixed success using the Wingscapes cameras, with several of them failing.

4 Results and discussion

4.1 CR23X clock drift

Every four hours, the CR23X MET data logger opened and closed solenoid valves that allowed the primary closed-path IRGA on the tower (LI-COR, model LI-6262) to sample a span gas and nitrogen (Monson et al., 2002). The MET data logger also creates a 1-Hz variable which records the status of the LI-6262 valves. Since the MET data logger CR23X clock would drift, the exact time the valves were opened and closed was always approximate, but known precisely from the valve-status variable. Lost 1-Hz data from the MET CR23X (Table 2) necessitated re-creating the valve-status variable, based on when the the LI-6262 IRGA sampled the nitrogen which was clearly defined because the LI-6262 CO_2 and H_2O drop sharply to zero as the nitrogen was sampled. By tracking the time of the calibration events we are essentially tracking the CR23X clock-drift, and found the MET logger clock typically drifted on the order of $-0.5\,\mathrm{sec\,day^{-1}}$ (Fig. 7). This clock drift-rate was an order of magnitude better then the worst-case CR23X specified clock drift of $\pm 4\,\mathrm{sec\,day^{-1}}$. Since we manually reset the data logger clocks on site visits (as described in Sect. 3.1 and shown by the step-changes back to near-zero offset in Fig. 7), we found that the CR23X clocks always tended to lag behind the actual time and none of the CR23Xs at our site experienced a positive clock drift.

4.2 Time stamp quality

As an independent check of the data-system clock, we used a CPEC200 and associated EC155 IRGA that were connected to a CR3000 data logger (with it's own GPS) that were added to the tower in September of 2013 (Burns et al., 2014). The CR3000 locally stored digital CO_2 from the EC155 that also output an analog CO_2 voltage into the FAST CR23X data logger (Table 2). When the difference between the 10-Hz analog CO_2 voltage and digital CO_2 are compared (Fig. 8), small pulse-like changes in the amplitude of the difference that have a period of anywhere from 2 to 6 hours can be observed. The CO_2 mole fraction has a typical mean value of around $400\,\mu$mol mol^{-1} and the differences shown in Fig. 9 are all smaller than $\pm 1\,\mu$mol mol^{-1}, suggesting that the CR23X analog sampling has an accuracy much better than $\pm\,0.25\%$. Furthermore, if the analog data are shifted forward and backward by one sample, the pulsed differences only occur when the analog data are shifted backward in time by one sample (red line in Fig. 8). Closer examination reveals that when the non-shifted data difference is at a minimum, the shifted data difference is at a maximum, and vice-versa. These characteristics suggest that the digital and analog CO_2 data have a slight time or phase-shift relative to each other.

To look further into this, the lag between the analog and digital EC155 CO_2 time series was calculated for each 30-min period from the phase (i.e., ratio of the quadrature spectrum to the cospectrum, Panofsky and Brier (1968); Piersol (1981)). The lag was estimated from the median of the phase within a frequency band of 0.05 to 3.3 Hz. The resulting estimated lag is shown for 2013 and 2014 over a five-day period in November when the ASTER/NDAQ software (Fig. 9a) and NIDAS software (Fig. 9b) were each being used. Here, we can observe more clearly that the lag between the EC155 analog CO_2 voltage and digital CO_2 were bounded by zero and -0.1 seconds, which corresponds to the sampling interval of the FAST CR23X. Though the clock drift in the CR23X doesn't affect the time-stamping of the individual data samples, it does affect the CR23X 10-Hz output into the data system, and reveals itself as a gradual change in the lag between zero and -0.1 seconds (Fig. 9). By counting the number of cycles on a given day we can estimate the daily clock drift-rate for the FAST CR23X data logger. For 2013, the drift rate was on the order of -0.25 sec day^{-1}. In 2014, the nominal drift rate was around -0.4 sec day^{-1}; however, during an extremely cold period (around day 316) the air temperature dropped below $-25\,°$C (Fig. 9c) and the clock drift rate increased to around -0.7 sec day^{-1}. This is consistent with the CR23X specifications that the clock drift rate is larger in cold conditions (described in Sect. 3.4). Though we cannot fully explain why the lag time differed in 2013 and 2014, the important result is that when either the ASTER/NDAQ or NIDAS configurations were being used, the CR23X logger samples were being properly time-tagged and the CR23X FAST logger lag was bounded by the sampling interval. Furthermore, though the phase difference would be important when making any calculations with a sensor independent from the FAST CR23X data logger; the lag should not have any effect on calculations using data which are strictly from the FAST data logger (i.e., for the eddy-covariance flux calculations).

4.3 Data system robustness

Because the goal of US-NR1 data collection was to have a continuous year-round time series of measured fluxes, one of the important data-system metrics is how much down-time or lost data occurred in the high-rate (10-Hz) data set. Table 3 summarizes the amount of lost or missing 10-Hz data by month and year. On average, there was about a 97% success rate for the high-frequency data collection. There were several months when the high-rate data loss exceeded 20% (highlighted in bold in Table 3); however, most of these occurred early on in the project. As noted in the footnotes of Table 3, most periods with lost data were caused by extended power outages or hardware failures. Since the Titan and NIDAS data system were deployed in October of 2014, the percentage of lost high-frequency data has been less than 0.02%.

An indication of how much effort it takes to run/manage an AmeriFlux site such as US-NR1 is provided in Table 3, where the number of annual site visits by the lead author ranged between a low of 19 in 2015 and a maximum of 93 in 2004. The years with a higher number of visits were typically when new instruments were being deployed, special field projects were taking place, and/or hardware or power problems problems occurred. The typical maximum time between site visits was approximately 3 weeks (with near-constant data-quality monitoring taking place from the CU campus using cockpit between the site visits).

Since the main tower is a metal object that is about twice the height of the surrounding forest, in a mountainous location with active convection during the warm-season, lightning is another consideration. When the tower was erected, Lightning Eliminators & Consultants, Inc. (http://www.lightningprotection.com/) installed a grounding system with two “spline-ball” terminals at the top of the tower connected to buried grounding rods at the base of the tower. Smaller ground rods surrounding the tower were connected to each other by solid copper wires. Though there has been lightning damage to components of the data system (mostly short-haul modems and the Edgeport/8 converter, through the power line), to the best of our knowledge, the tower has never taken a direct lightning hit. We have found that powering the CR23X data loggers with deep-cycle batteries provides some degree of lightning protection and also allows them to keep on saving the internal 5-min mean averages (useful for gap-filling) during power outages. We also found that lifting data cables off the ground reduced collateral damage (e.g., electrical damage to short-haul modems) when lightning struck near the tower. Either fiber optic cables or wireless data transmission would be another way to minimize problems with lightning.

Though the CR23X is somewhat older technology (production of the CR23X stopped around 2007), these data loggers have proven to be an extremely durable, stable part of the US-NR1 data system. In collecting the 10-Hz data, we have pushed the CR23Xs to the point where it can barely keep up with the data-collection demands. For example, the FAST CR23X has been typically used to ingest data from three SDM sensors (two CSAT3 sonic anemometers and one LI-7500 IRGA) along with data from 7 differential and 4 single-ended analog channels. Adding additional sensors to the FAST CR23X would not allow it to complete the full measurement cycle in 0.1 seconds. The only maintenance for the CR23Xs has been the replacement of the internal battery after about 10 years. We should also consider periodically checking the analog-to-digital converter, but empirical evidence (such as that presented in Sect. 4.2) suggest they are fairly stable.

One downside to the CR23X is that it cannot sample at 10-Hz and use a GPS to keep the internal clock from drifting. If the CR23Xs were upgraded to a more recent data logger (such as the CR3000) then a GPS could be used to keep the internal data logger clock from drifting. However, as described in Sect. 4.2, because the CR23Xs are coupled with NCAR EOL data-acquisition software and hardware (running NTP), the data samples from the CR23X are time-tagged by the data system, making the CR23X internal clock less important.

5 Summary and conclusions

We found that high-rate (10-Hz) eddy-covariance data collection from multiple off-the-shelf data loggers at Niwot Ridge Subalpine Forest US-NR1 AmeriFlux site was made more manageable by using a centralized computer and data-acquisition software developed at the NCAR Earth Observing Laboratory (https://www.eol.ucar.edu/). Using a centralized computer allowed for: consistent data storage, robust time stamps, and a flexible, real-time calculation of statistics. The EOL software also contained a real-time display that allowed all the measured variables to be displayed at once (i.e., cockpit shown in Fig. 3). All these features helped to quickly alert tower staff of any potential instrument or data-system problems and minimize the amount of lost high-rate data.

Though the data-collection philosophy has remained similar over the 17-plus years of US-NR1 operation, the hardware and software for data-collection has evolved and incorporated considerable improvements (with an ultimate goal of creating a data-acquisition system that operates as long as power is available). We worked to achieve this goal by replacing a data-acquisition system that depended on two computers and the network for time-stamping (Fig. 1) with a data-acquisition system that depended on a single PC/104-based computer and used a network-independent GPS for time-stamping (Fig. 2). These changes resulted in a more robust collection of high-frequency data. Over 17 years, the average high-rate data-collection success rate was $\approx 97\%$, which increased to better than 99.98% (Table 3) since the upgrades. Furthermore, by powering the data loggers with external deep-cycle batteries, it was possible to continue collecting the mean meteorological measurements that are useful for gap-filling flux data during power outages.

A useful data-system-integrity check was to sample data from an independent data system and compare the sampled-data with time series from the other system for mean/offset and time-stamp differences. From this test, we found that the CR23X data-logger clock drift created a small time lag in the eddy-covariance high-frequency data that was equal to or less than the sampling period of 0.1 s. The time lag will not impact the flux calculations because the eddy-covariance variables are all measured with a single CR23X. Finally, we outlined the techniques that we have employed to record and preserve the activities and metadata at the site (including web-based calendars and logbooks, as well as photos). We strongly recommend that careful consideration be given to site documentation and metadata information at the outset of any long-term measurement campaign. Furthermore, already-established protocols (e.g., Papale et al., 2012) should be followed as closely as possible at the start of the project. A snapshot of the current state of the US-NR1 metadata as well as the data-acquisition software used are provided within the supplemental material of this paper.

Software, Logger Code, and Documentation

In the supplemental material we provide the following items:

- USNR1_logger_code.zip: All versions of the CR23X and CR10X data logger programs
- USNR1_webcalendar.zip: The web calendar HTML files
- USNR1_webphoto.zip: The HTML files used for the site photos (and links in the web calendar pages)

- USNR1_logbook.zip: The logbook (in both native and HTML format)
- USNR1_OPS_aster.zip: The OPS files used with ASTER/ADAM-ATI and ASTER/NDAQ
- USNR1_OPS_nidas.zip: The OPS files used with NIDAS
- USNR1_nidas_isffa.zip: The NIDAS software package running on isffa
- USNR1_nidas_urquell.zip: The NIDAS software package running on urquell
- USNR1_aster_ndaq.zip: Source code for ASTER software which ran on russter2 and NDAQ which ran on the quacker
- USNR1_5minute_statistics_files.zip: Examples of daiily netCDF data files with 5-min statistics
- USNR1_prep.zip: Examples of running prep on urquell to extract the raw data in ASCII for both the ASTER/NDAQ and NIDAS configurations
- USNR1_ati_duck_manual.pdf: PDF of the manual for the duck data acquisition system (using ADAM-ATI)

Each zip archive has a corresponding README file with more details related to the files within the archive.

Acknowledgements. Andrew Tunipseed designed and implemented the original instrument and data system setup at the US-NR1 site. Jeff Beauregard assisted with site operations in 2007–2008. Many people at NCAR EOL helped with information related to US-NR1 infrastruction and instruments, especially Tom Horst, Tony Delany, John Militzer, and Kurt Knudson. Jielun Sun (NCAR) kindly shared a CR23X logger (and associated themocouples). Chris Golubieski (formerly of EOL, now at NREL) helped with the setup of Titan/PC-104 hardware and enclosure. Edward Swiatek and others at Campbell Scientific, Inc. setup the CPEC200 and generously shared those data with us. The Niwot Ridge LTER (Mark Williams) provided the initial "forestcam" and Andrew Richardson (Harvard University) and the University of New Hampshire PhenoCam network provided subsequent cameras. Mark Raleigh (CIRES) provided advice/discussions about the Wingscapes cameras. Gilberto Pastorello helped with archiving of raw data files. The UnixOPS computer support group at CU (led by Orrie Gartner) were a tremendous help with the Linux/system OS and networking advice. The US-NR1 AmeriFlux site is currently supported by the U.S. DOE, Office of Science through the AmeriFlux Management Project (AMP) at Lawrence Berkeley National Laboratory under Award Number 7094866. The National Center for Atmospheric Research (NCAR) is sponsored by NSF.

References

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalski, A. S., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grunwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., and Vesala, T.: Estimates of the annual net carbon and water exchange of forests: The EUROFLUX methodology, Adv. Ecol. Res., 30, 113–175, 2000.

Aubinet, M., Vesala, T., and Papale, D.: Eddy Covariance: A Practical Guide to Measurement and Data Analysis, Springer Atmospheric Sciences, Dordrecht, The Netherlands, 438 pp., 2012.

Baldocchi, D., Falge, E., Gu, L. H., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X. H., Malhi, Y., Meyers, T., Munger, W., Oechel, W., U, K. T. P., Pilegaard, K., Schmid, H. P., Valentini, R., Verma, S., Vesala, T., Wilson, K., and Wofsy, S.: FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities, Bull. Amer. Meteor. Soc., 82, 2415–2434, 2001.

Behn, M., Hohreiter, V., and Muschinski, A.: A scalable datalogging system with serial interfaces and integrated GPS time stamping, J. Atmos. Oceanic Technol., 25, 1568–1578, 2008.

Billesbach, D. P., Fischer, M. L., Torn, M. S., and Berry, J. A.: A portable eddy covariance system for the measurement of ecosystem-atmosphere exchange of CO_2, water vapor, and energy, J. Atmos. Oceanic Technol., 21, 639–650, 2004.

Boden, T. A., Krassovski, M., and Yang, B.: The AmeriFlux data activity and data system: an evolving collection of data management techniques, tools, products and services, Geosci. Instrum. Method. Data Syst., 2, 165–176, doi:10.5194/gi-2-165-2013, 2013.

Burba, G.: Eddy Covariance Method for Scientific, Industrial, Agricultural, and Regulatory Applications: A Field Book on Measuring Ecosystem Gas Exchange and Areal Emission Rates, LI-COR Biosciences, Lincoln, NE, USA, 331 pp., 2013.

Burns, S. P., Molotch, N. P., Williams, M. W., Knowles, J. F., Seok, B., Monson, R. K., Turnipseed, A. A., and Blanken, P. D.: Snow temperature changes within a seasonal snowpack and their relationship to turbulent fluxes of sensible and latent heat, J. Hydrometeor., 15, 117–142, doi:10.1175/JHM-D-13-026.1, 2013.

Burns, S. P., Metzger, S., Blanken, P. D., Burba, G. G., Swiatek, E., Li, J., Conrad, B., Luo, H., and Taylor, J.: A comparison of infrared gas analyzers above a subalpine forest in complex terrain, in: 17th Symposium on Meteorological Observation and Instrumentation, Westminister, CO. American Meteorological Society, 13, URL: https://ams.confex.com/ams/21Applied17SMOI/, 2014.

Burns, S. P., Blanken, P. D., Turnipseed, A. A., Hu, J., and Monson, R. K.: The influence of warm-season precipitation on the diel cycle of the surface energy balance and carbon dioxide at a Colorado subalpine forest site, Biogeosciences, 12, 7349–7377, doi:10.5194/bg-12-7349-2015, 2015.

Burns, S. P., Blanken, P. D., Harpold, A. A., Molotch, N. P., Moore, D. J. P., Williams, M. W., and Monson, R. K.: The Niwot Ridge Subalpine Forest US-NR1 AmeriFlux site – Part II: Site characteristics, Hydrol. Earth Syst. Sc., to be submitted, 2016.

Businger, J. A., Dabberdt, W. F., Delany, A. C., Horst, T. W., Martin, C. L., Oncley, S. P., and Semmer, S. R.: The NCAR Atmosphere-Surface Turbulent Exchange Research (ASTER) facility, Bull. Amer. Meteor. Soc., 71, 1006–1011, 1990.

Campbell Scientific, Inc.: CR23X Micrologger Operators Manual (Revision 11/06), Logan, Utah, 374 pp., [https://www.campbellsci.com/cr23x], 2006.

Campbell Scientific, Inc.: EC155 CO_2 and H_2O Closed-Path Gas Analyzer Instruction Manual (Revision 5/13), Logan, Utah, 66 pp, [https://www.campbellsci.com/ec155], 2013.

Emeis, S.: Measurement Methods in Atmospheric Sciences, Borntraeger Science Publishers, Stuttgart, Germany, 257 pp., 2010.

Foken, T., Leuning, R., Oncley, S., Mauder, M., and Aubinet, M.: Corrections and data quality control, in: Eddy Covariance: A Practical Guide to Measurement and Data Analysis, edited by Aubinet, M., Vesala, T., and Papale, D., pp. 85–131, Springer Atmospheric Sciences, 2012.

Gochis, D., Schumacher, R., Friedrich, K., Doesken, N., Kelsch, M., Sun, J., Ikeda, K., Lindsey, D., Wood, A., Dolan, B., Matrosov, S., Newman, A., Mahoney, K., Rutledge, S., Johnson, R., Kucera, P., Kennedy, P., Sempere-Torres, D., Steiner, M., Roberts, R., Wilson, J., Yu, W., Chandrasekar, V., Rasmussen, R., Anderson, A., and Brown, B.: The Great Colorado Flood of September 2013, Bull. Amer. Meteor. Soc., 96, 2014.

Göckede, M., Foken, T., Aubinet, M., Aurela, M., Banza, J., Bernhofer, C., Bonnefond, J. M., Brunet, Y., Carrara, A., Clement, R., Dellwik, E., Elbers, J., Eugster, W., Fuhrer, J., Granier, A., Grünwald, T., Heinesch, B., Janssens, I. A., Knohl, A., Koeble, R., Laurila, T., Longdoz, B., Manca, G., Marek, M., Markkanen, T., Mateus, J., Matteucci, G., Mauder, M., Migliavacca, M., Minerbi, S., Moncrieff, J., Montagnani, L., Moors, E., Ourcival, J.-M., Papale, D., Pereira, J., Pilegaard, K., Pita, G., Rambal, S., Rebmann, C., Rodrigues, A., Rotenberg, E., Sanz, M. J., Sedlak, P., Seufert, G., Siebicke, L., Soussana, J. F., Valentini, R., Vesala, T., Verbeeck, H., and Yakir, D.: Quality control of CarboEurope flux data – Part 1: Coupling footprint analyses with flux data quality assessment to evaluate sites in forest ecosystems, Biogeosciences, 5, 433–450, doi:10.5194/bg-5-433-2008, 2008.

IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems, IEEE Std 1588-2002, pp. i–144, doi:10.1109/IEEESTD.2002.94144, 2002.

Illingworth, A. J., Hogan, R. J., O'Connor, E. J., Bouniol, D., Delanoë, J., Donovan, D. P., Gaussiat, N., Goddard, J. W. F., Haeffelin, M., Baltink, H. K., Krasnov, O. A., Pelon, J., Piriou, J.-M., Protat, A., Russchenberg, H. W. J., Seifert, A., Tompkins, A. M., van Zadelhoff, G.-J., Vinit, F., Willén, U., Wilson, D. R., and Wrench, C. L.: Cloudnet, Bull. Amer. Meteor. Soc., 88, 883–898, doi:10.1175/BAMS-88-6-883, 2007.

Kaimal, J. C. and Finnigan, J. J.: Atmospheric Boundary Layer Flows: Their Structure and Measurement, Oxford University Press, New York, 289 pp., 1994.

Keenan, T. F., Darby, B., Felts, E., Sonnentag, O., Friedl, M. A., Hufkens, K., O'Keefe, J., Klosterman, S., Munger, J. W., Toomey, M., and Richardson, A. D.: Tracking forest phenology and seasonal physiology using digital repeat photography: a critical assessment, Ecological Applications, 24, 1478–1489, doi:10.1890/13-0652.1, 2014.

Lombardi, M. A., Nelson, L. M., Novick, A. N., and Zhang, V. S.: Time and frequency measurements using the Global Positioning System, Cal. Lab. Int. J. Metrology, 8, 26–33, 2001.

Maclean, G. and Webster, C.: NCAR In-Situ Data Acquisition Software for Airborne and Surface Measurements, in: 16th Symposium on Meteorological Observation and Instrumentation, New Orleans, LA. American Meteorological Society, 10.1, URL: https://ams.confex.com/ams/92Annual/webprogram/, 2012.

Massman, W. J. and Lee, X.: Eddy covariance flux corrections and uncertainties in long term studies of carbon and energy exchanges, Agric. For. Meteor., 113, 121–144, 2002.

Matese, A., Alberti, G., Gioli, B., Toscano, P., Vaccari, F. P., and Zaldei, A.: Compact_Eddy: A compact, low consumption remotely controlled eddy covariance logging system, Comput. Electron. Agr., 64, 343–346, 2008.

Mauder, M., Foken, T., Clement, R., Elbers, J. A., Eugster, W., Grunwald, T., Heusinkveld, B., and Kolle, O.: Quality control of CarboEurope flux data – Part 2: Inter-comparison of eddy-covariance software, Biogeosciences, 5, 451–462, 2008.

Monson, R. K., Turnipseed, A. A., Sparks, J. P., Harley, P. C., Scott-Denton, L. E., Sparks, K., and Huxman, T. E.: Carbon sequestration in a high-elevation, subalpine forest, Global Change Biol., 8, 459–478, 2002.

Oncley, S. P.: Flux parameterization techniques in the atmospheric surface layer, Ph.D. thesis, University of California, Irvine, Irvine, CA, USA, 202 pp., 1989.

Panofsky, H. A. and Brier, G. W.: Some Applications of Statistics to Meteorology, Earth and Mineral Sciences Continuing Education, College of Earth and Mineral Sciences, The Pennsylvania State University, 224 pp., 1968.

Papale, D.: Data gap filling, in: Eddy Covariance: A Practical Guide to Measurement and Data Analysis, edited by Aubinet, M., Vesala, T., and Papale, D., pp. 159–172, Springer Atmospheric Sciences, 2012.

Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W., Longdoz, B., Rambal, S., Valentini, R., Vesala, T., and Yakir, D.: Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: algorithms and uncertainty estimation, Biogeosciences, 3, 571–583, 2006.

Papale, D., Agarwal, D. A., Baldocchi, D., Cook, R. B., Fisher, J. B., and van Ingen, C.: Database Maintenance, Data Sharing Policy, Collaboration, in: Eddy Covariance: A Practical Guide to Measurement and Data Analysis, edited by Aubinet, M., Vesala, T., and Papale, D., pp. 399–424, Springer Atmospheric Sciences, 2012.

Piersol, A.: Time delay estimation using phase data, IEEE Transactions on Acoustics, Speech, and Signal Processing, 29, 471–477, doi:10.1109/TASSP.1981.1163555, 1981.

Rebmann, C., Heinesch, B., Queck, R., Ibrom, A., and Aubinet, M.: Data acquisition and flux calculations, in: Eddy Covariance: A Practical Guide to Measurement and Data Analysis, edited by Aubinet, M., Vesala, T., and Papale, D., pp. 59–83, Springer Atmospheric Sciences, 2012.

Refan, M. H. and Valizadeh, H.: Computer network time synchronization using a low cost GPS engine, Iran. J. Electr. Electron. Eng., 8, 206–216, 2012.

Schween, J. H., Kuettner, J., Reinert, D., Reuder, J., and Wirth, V.: Definition of "banner clouds" based on time lapse movies, Atmos. Chem. Phys, 7, 2047–2055, doi:10.5194/acp-7-2047-2007, 2007.

Turnipseed, A. A., Blanken, P. D., Anderson, D. E., and Monson, R. K.: Energy budget above a high-elevation subalpine forest in complex topography, Agric. For. Meteor., 110, 177–201, 2002.

UCAR/NCAR–Earth Observing Laboratory: NCAR Integrated Suface Flux System (ISFS), doi:10.5065/D6ZC80XJ, 1990-present.

Unidata: NetCDF version 4.4.0 [software], Boulder, CO: UCAR/Unidata, doi:10.5065/D6H70CW6, 2016.

Van Atta, C. W.: Sampling Techniques in Turbulence Measurements, Annu. Rev. Fluid Mech., 6, 75–91, 1974.

van der Molen, M. K., Zeeman, M. J., Lebis, J., and Dolman, A. J.: EClog: A handheld eddy covariance logging system, Comput. Electron. Agr., 51, 110–114, 2006.

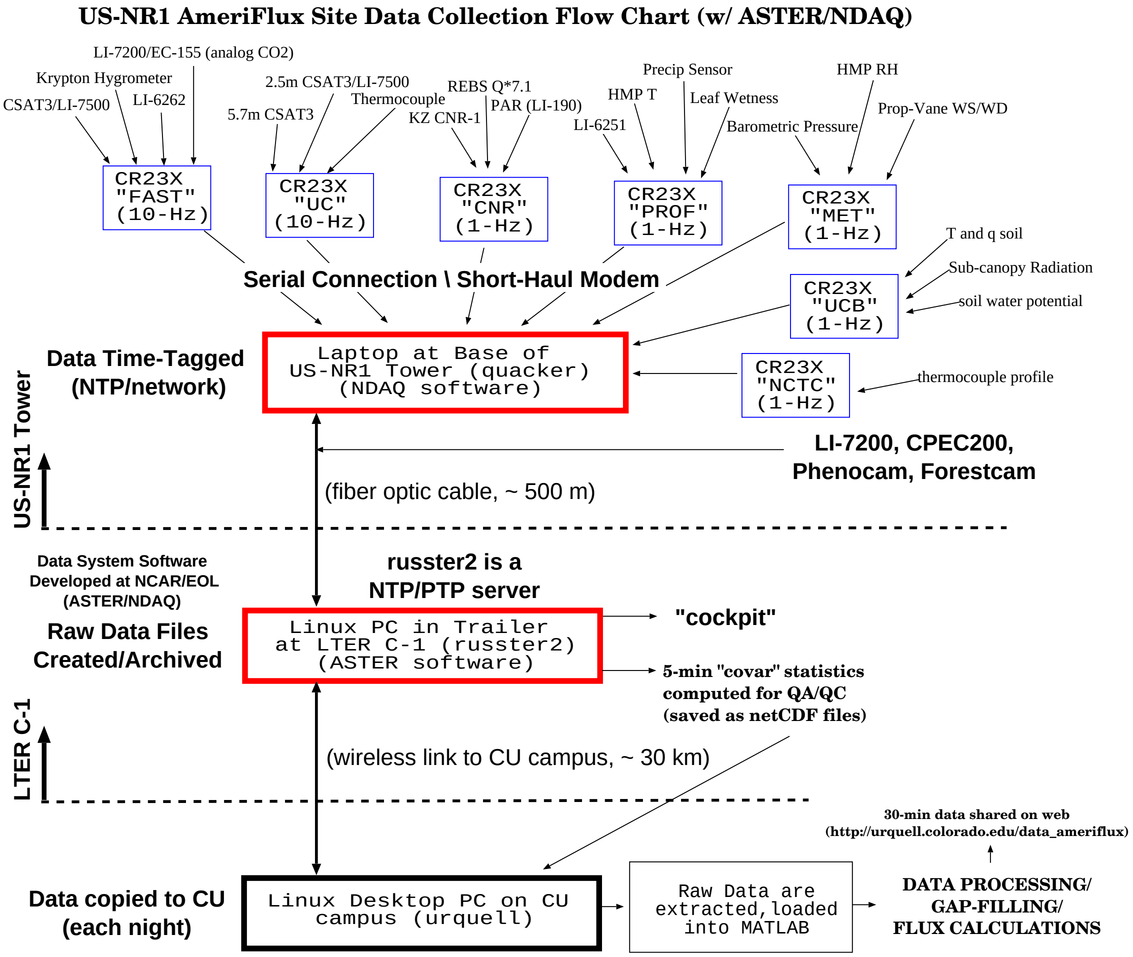


Figure 1. Schematic flow chart of data collection with the ASTER/NDAQ data acquisition software which was used between June 2004 and October 2014 at the Niwot Ridge US-NR1 AmeriFlux site. The data flow is from the instruments (at the top of the chart), to the CR23X data loggers, to a laptop (quacker) at the tower for time-tagging, to a desktop computer (russter2) in the trailer at LTER C-1 for archiving, followed by nightly copying of the raw data files to the server on CU campus (urquell). The horizontal dashed lines represent spatial separation of hardware locations; distances are noted in the schematic (the upper portion of the schematic is at the US-NR1 tower, the middle portion at LTER C-1, and the lower portion on the CU campus). The red boxes indicate high-rate data system components that are discussed within the text (Sect. 3.2.2)

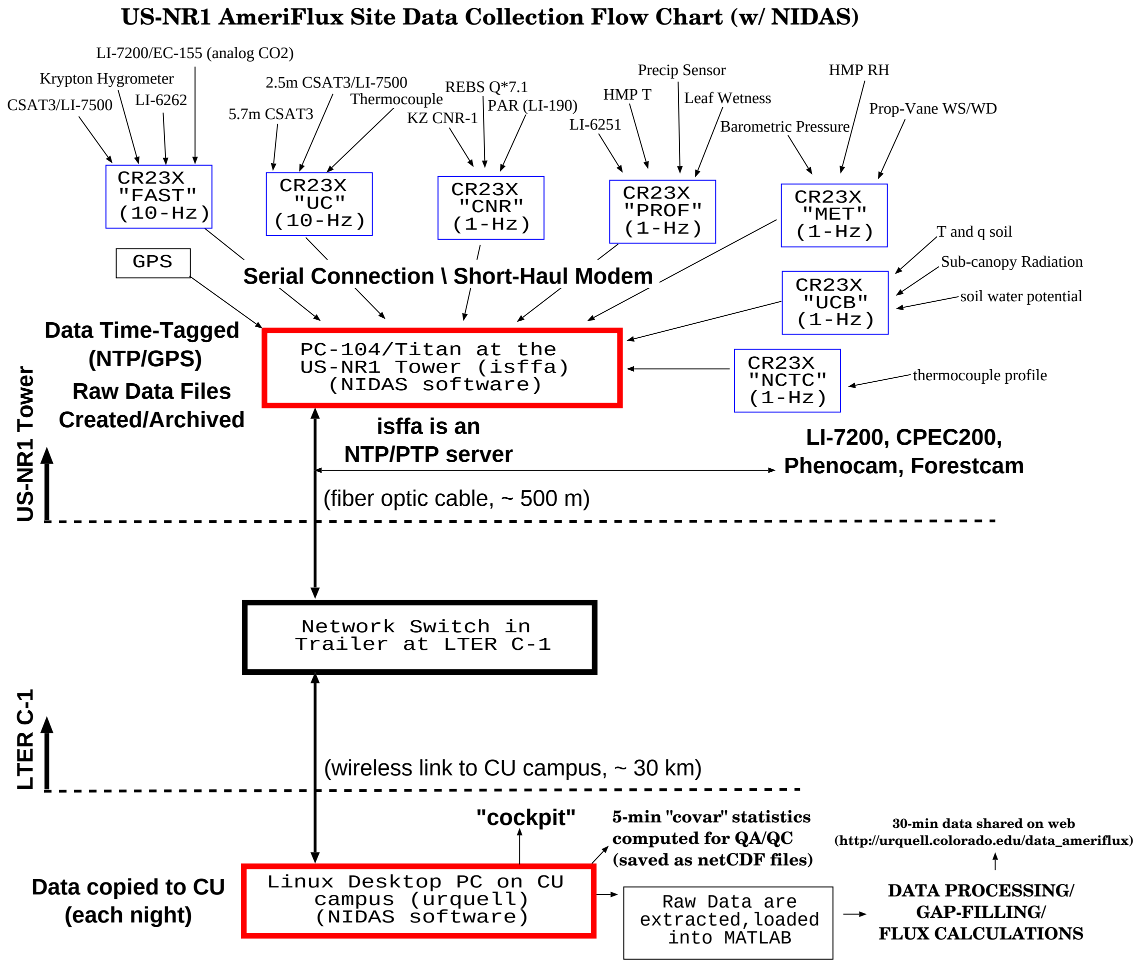


Figure 2. As in Fig. 1, except showing the data flow with the NIDAS data acquisition system, which was used starting on 20 October 2014. With the NIDAS system, the computer in the trailer at LTER C-1 (russter2) is replaced with a network switch/hub. The red boxes indicate high-rate data system components that are discussed within the text (Sect. 3.2.3).

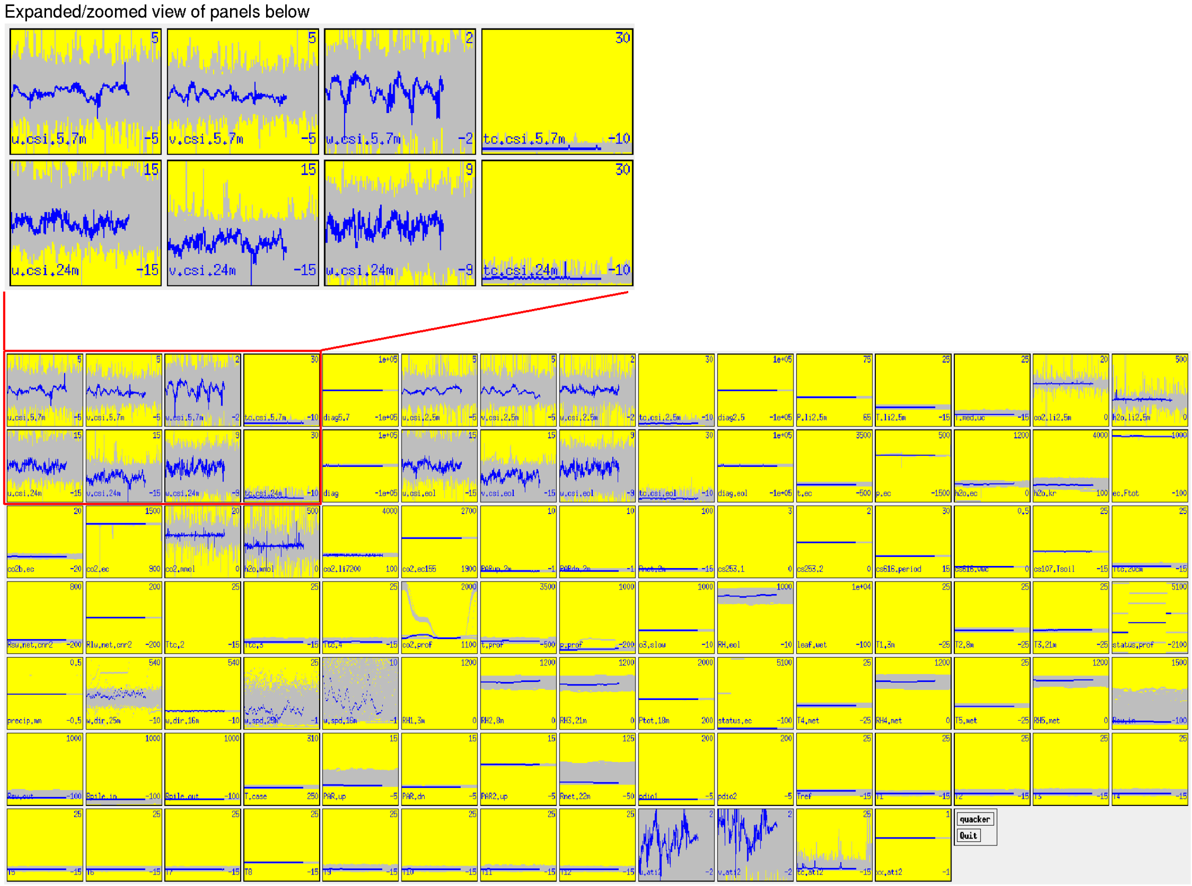
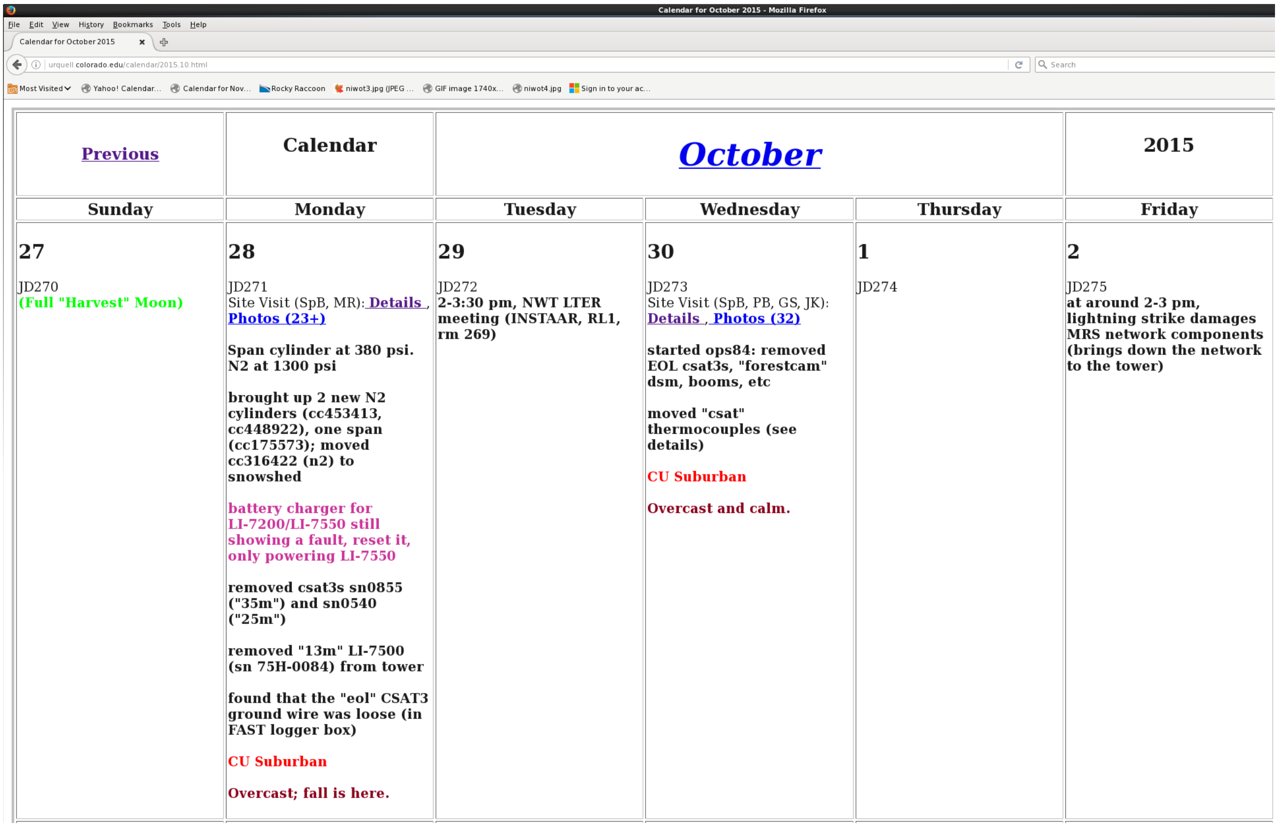
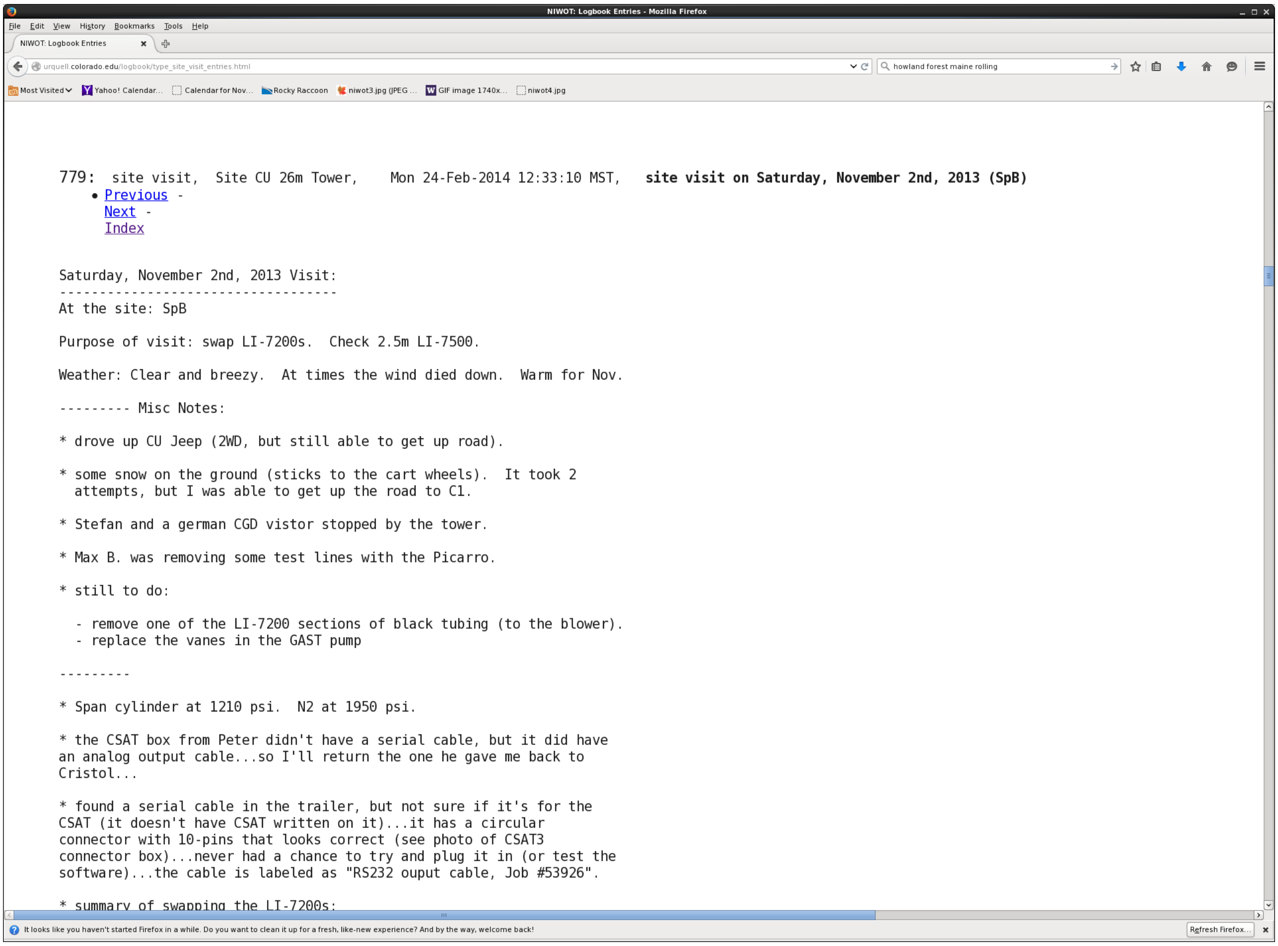


Figure 3. Screenshot of data monitoring software (cockpit) from 7 February, 2014. Each box shows data from an individual sensor where the blue line is the current, real-time data being collected and the grey background is the trace of data collected since the cockpit session was initiated. The upper set of inset panels offer an enlarged view of the 8 panels outlined in red in the upper right-hand corner of the cockpit window; here, the wind components and temperature measured by two CSAT3 sonic anemometers with base variable names: u, v, w, and tc are shown.



Previous	**Calendar**	***October***			**2015**
Sunday	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
27 JD270 **(Full "Harvest" Moon)**	**28** JD271 Site Visit (SpB, MR): **Details** , **Photos (23+)** **Span cylinder at 380 psi. N2 at 1300 psi** **brought up 2 new N2 cylinders (cc453413, cc448922), one span (cc175573); moved cc316422 (n2) to snowshed** **battery charger for LI-7200/LI-7550 still showing a fault, reset it, only powering LI-7550** **removed csat3s sn0855 ("35m") and sn0540 ("25m")** **removed "13m" LI-7500 (sn 75H-0084) from tower** **found that the "eol" CSAT3 ground wire was loose (in FAST logger box)** **CU Suburban** **Overcast; fall is here.**	**29** JD272 **2-3:30 pm, NWT LTER meeting (INSTAAR, RL1, rm 269)**	**30** JD273 Site Visit (SpB, PB, GS, JK): **Details** , **Photos (32)** **started ops84: removed EOL csat3s, "forestcam" dsm, booms, etc** **moved "csat" thermocouples (see details)** **CU Suburban** **Overcast and calm.**	**1** JD274	**2** JD275 **at around 2-3 pm, lightning strike damages MRS network components (brings down the network to the tower)**

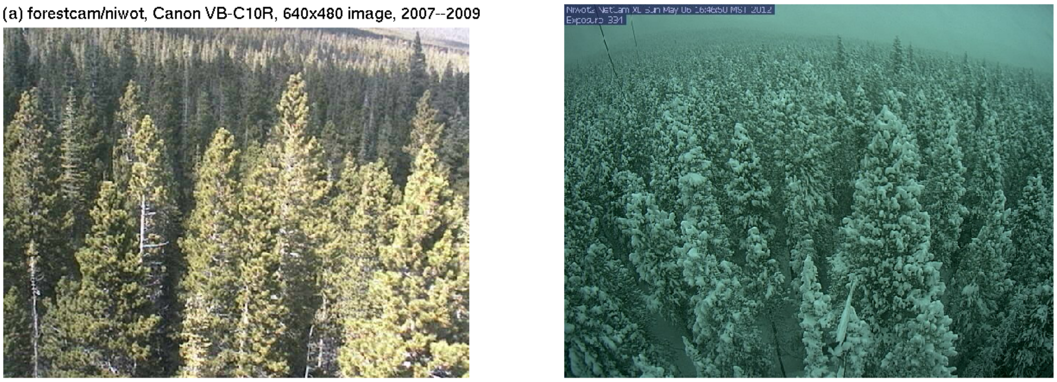
Figure 4. A screenshot example of the US-NR1 web calendar from October, 2015. The web calendar includes a color-coded short summary of activities done the site as well as links to photos and a more detailed logbook entry of the visit. The web-calendar is accessible on-line at http://urquell.colorado.edu/calendar/.



```
779:  site visit,  Site CU 26m Tower,    Mon 24-Feb-2014 12:33:10 MST,   site visit on Saturday, November 2nd, 2013 (SpB)
      • Previous -
        Next -
        Index


Saturday, November 2nd, 2013 Visit:
-----------------------------------
At the site: SpB

Purpose of visit: swap LI-7200s.  Check 2.5m LI-7500.

Weather: Clear and breezy.  At times the wind died down.  Warm for Nov.

--------- Misc Notes:

* drove up CU Jeep (2WD, but still able to get up road).

* some snow on the ground (sticks to the cart wheels).  It took 2
  attempts, but I was able to get up the road to C1.

* Stefan and a german CGD vistor stopped by the tower.

* Max B. was removing some test lines with the Picarro.

* still to do:

  - remove one of the LI-7200 sections of black tubing (to the blower).
  - replace the vanes in the GAST pump

---------

* Span cylinder at 1210 psi.  N2 at 1950 psi.

* the CSAT box from Peter didn't have a serial cable, but it did have
an analog output cable...so I'll return the one he gave me back to
Cristol...

* found a serial cable in the trailer, but not sure if it's for the
CSAT (it doesn't have CSAT written on it)...it has a circular
connector with 10-pins that looks correct (see photo of CSAT3
connector box)...never had a chance to try and plug it in (or test the
software)...the cable is labeled as "RS232 ouput cable, Job #53926".

* summary of swapping the LI-7200s:
```

It looks like you haven't started Firefox in a while. Do you want to clean it up for a fresh, like-new experience? And by the way, welcome back!

Figure 5. A screenshot example of the US-NR1 logbook entry from 2 November, 2013. The logbook is accessible on-line at http://urquell.colorado.edu/logbook/.

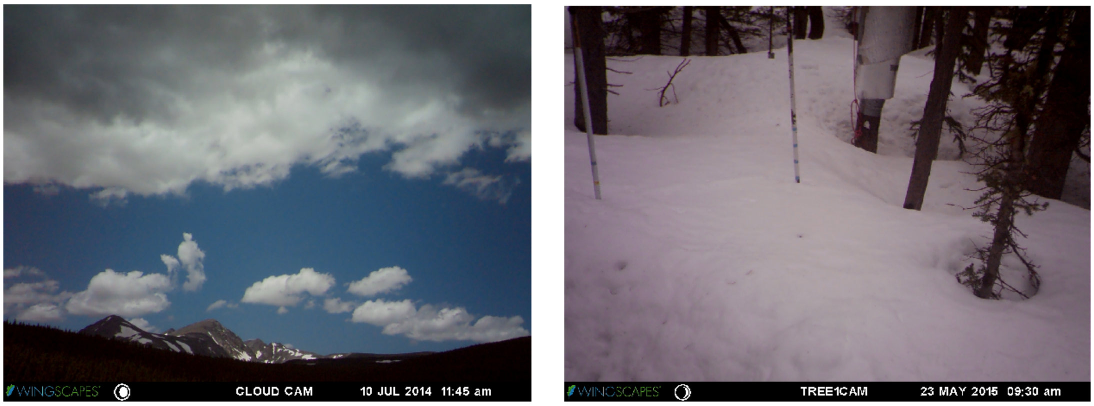


(a) forestcam/niwot, Canon VB-C10R, 640x480 image, 2007--2009

(b) niwot2, StarDot NetCam XL, 672x512 image, 2009--2015

(c) niwot3, StarDot NetCam SC/IR, 1296x960 image, 2015--present

(d) niwot4, StarDot NetCam XL, 672x512 image, 2015--present



(e) cloudcam, Wingscapes TimelapseCam, 2592x1944, 2014--present

(f) tree1cam, Wingscapes TimelapseCam, 1600x1200, 2014--present

Figure 6. Example photos from different webcams installed on the US-NR1 tower. The camera name, camera type, raw image size, and dates of operation are provided above each photo. Cameras niwot, niwot2, niwot3, and tree1cam are all pointed north, niwot4 is looking east, and the cloudcam is looking west. The cameras niwot2 and niwot4 are the same physical camera. Images from niwot, niwot2, niwot3, and niwot4 are all available from the University of New Hampshire PhenoCam project website (http://phenocam.sr.unh.edu/webcam/). The cloudcam and tree1cam cameras were not capturing images for the entire period shown.

Geosci. Instrum. Method. Data Syst. Discuss., doi:10.5194/gi-2016-17, 2016
Manuscript under review for journal Geosci. Instrum. Method. Data Syst.
Published: 14 June 2016

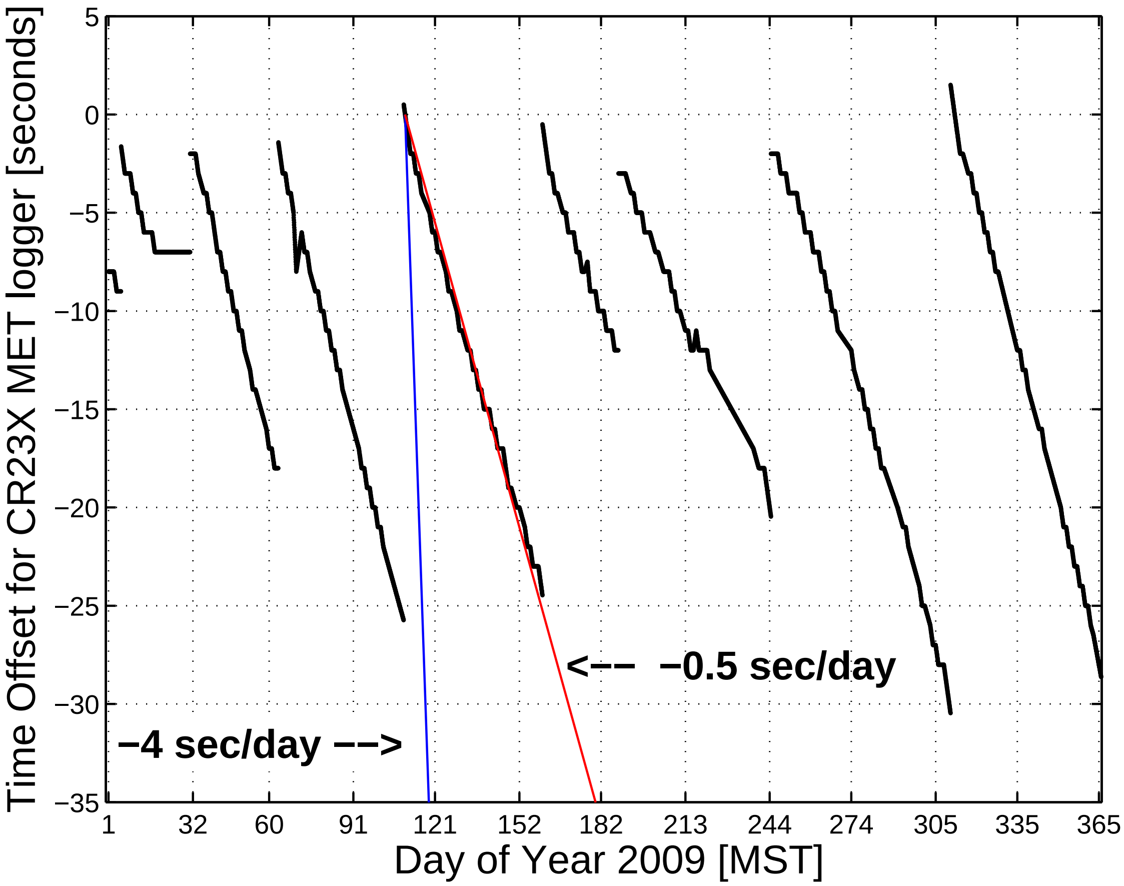


Figure 7. Time series of the estimated time offset between the CR23X MET data logger clock and the data system clock in 2009 (a negative offset indicates that the MET logger time lagged behind the data system time). The offset is calculated based on the time of the LI-6262 calibration which is controlled by the MET data logger and programmed to occur every four hours, starting at midnight. On average, the drift in the CR23X clock was approximately $-0.5\,\mathrm{sec\,day^{-1}}$. The blue line indicates the CR23X worst-case clock drift specification of $-4\,\mathrm{sec\,day^{-1}}$ (i.e., $-2\,\mathrm{min\,month^{-1}}$ for temperatures between -40 and $-25\,^{\circ}\mathrm{C}$) while the red line corresponds to a clock drift of $-0.5\,\mathrm{sec\,day^{-1}}$. The sharp drops back toward zero occurred when the CR23X clock was manually reset during site visits.

Geosci. Instrum. Method. Data Syst. Discuss., doi:10.5194/gi-2016-17, 2016
Manuscript under review for journal Geosci. Instrum. Method. Data Syst.
Published: 14 June 2016

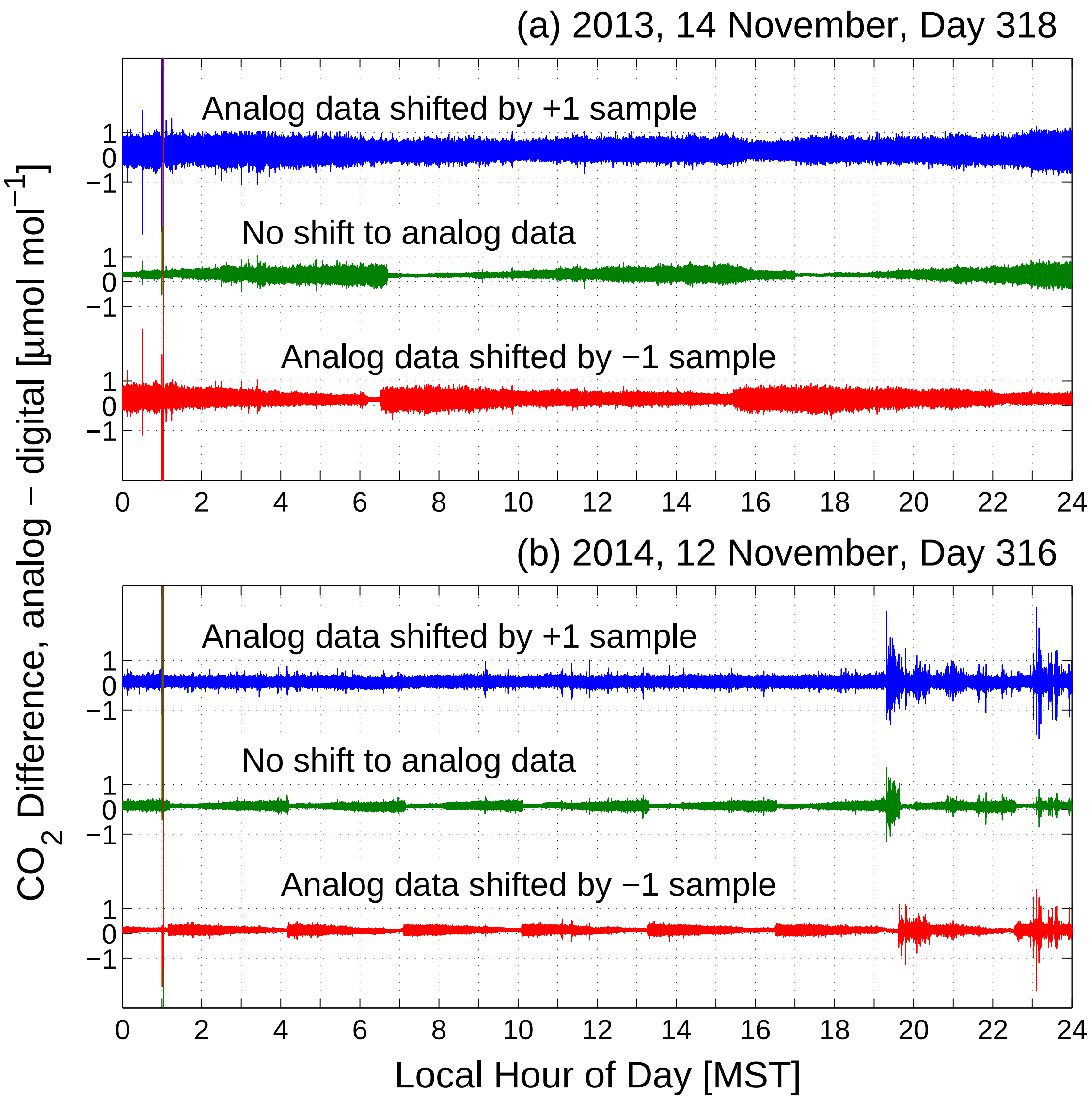


Figure 8. A time series of the difference between the 10-Hz analog EC155 CO_2 measured by the US-NR1 data system and the 10-Hz digital EC155 CO_2 data saved on the CR3000 for **(a)** 14 November 2013 and **(b)** 12 November 2014. The differences are shown where the analog samples have been shifted by 1 sample forward and backward in time as described by the text above the time series.

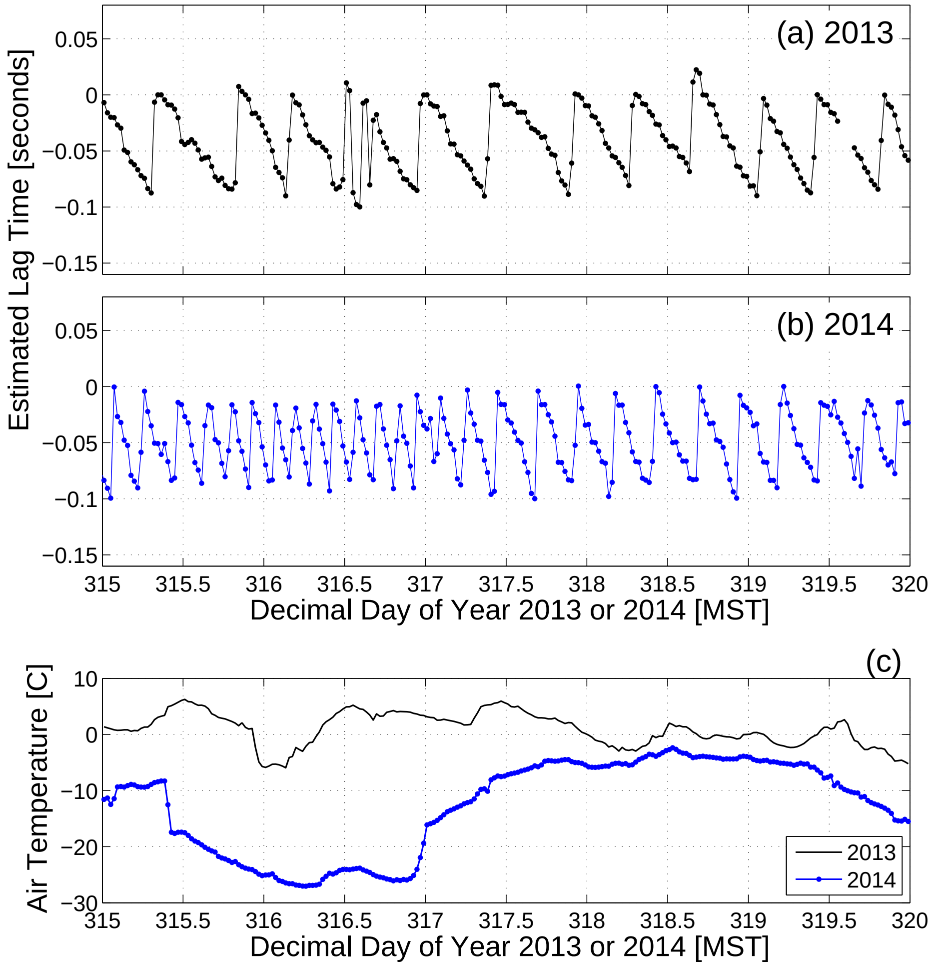


Figure 9. Time series of the estimated lag time between the analog and digital signal of the CO_2 dry mole fraction from the EC155 IRGA for **(a)** 2013 and **(b)** 2014. In **(c)**, the 21.5 m air temperature from both years is shown (see legend). The analog voltage is ingested into the data system by the FAST CR23X data logger while the digital signal is archived on a CR3000 connected to the EC155.

Table 1. A chronological summary of changes to the US-NR1 data acquistion hardware and software.

	Hardware Systems[a]				
Date	At US-NR1 Tower	At C-1 Trailer	Software	Time-keeping	Additional Comments
1 Nov 1998	PC/486 (Linux) Rocketport serial card (**duck**)	Sun SPARCstation 5 (**russter.colorado.edu**)	ASTER/ADAM-ATI[b]	Network w/ NTP	ADAM-ATI was a data acquistion system/board from Applied Technologies Inc. (http://www.apptech.com/) using a Rocketport multi-port serial card
2 Aug 2002	Dell Inspiron 7000, Edgeport/8 converter (**quacker**)	No Hardware Change	ASTER/ADAM-ATI[b]	Network w/ NTP	Dell laptop, http://www.dell.com/ Edgeport/8 USB-to-Serial Converter (w/ 8 DE-9 ports), http://www.digi.com/products/models/301-1002-08
18 Jun 2004	No Hardware Change	Dell Precision PC (**russter2.colorado.edu**)	ASTER/NDAQ[c]	Network w/ NTP	Dell Precision Workstation 360n Minitower, https://en.wikipedia.org/wiki/Dell_Precision
20 Oct 2014	Eurotech PC/104 Titan, Emerald 8P Module (**isffa.colorado.edu**)	No Longer Necessary	NIDAS[d]	GPS w/ NTP	Eurotech PC/104 single board computer, http://www.eurotech.com/en/products/TITAN Emerald-MM-8P 8-Port Serial Module, http://www.diamondsystems.com/products/emeraldmm8p

[a] Parenthetical items in bold are either the local or network name of the associated hardware which will be referred to within the text and throughout our study

[b] The NCAR Atmospher-Surface Turbulent Exchange Research (ASTER) facility uses Automatic Data-Acquisition Modules (ADAMS) to collect data from remote locations and send them to a base station (Businger et al., 1990). Specific details about the ADAM-ATI used at the US-NR1 tower are in Sect. 3.2.1 in the text, and within the supplemental material (USNR1_ati_duck_manual.pdf).

[c] NDAQ stands for the NCAR Data Acquisition system (see Sect. 3.2.2 in text for details)

[c] The NCAR In-Situ Data Acquisition Software (NIDAS) is open-source software developed by the NCAR Earth Observing Laboratory (see Sect. 3.2.3 in text for details). Current NIDAS information is available on github, https://github.com/ncareol/nidas/wiki

Table 2. Campbell Scientific data loggers used at the US-NR1 AmeriFlux site. The loggers are listed by the approximate date they were installed on the tower. The logger programs are listed such that only the latest version of the code is shown (for example, fast_24.csi means there are 24 versions of the FAST logger program since this naming scheme was initiated). The SOIL, TC, and MRS loggers are not connected to the high-rate data system.

Logger Name	Model	Logger Location	Current Logger Program	Output Data Details		Data Period^{b}	Notes
				Ingested by Data System	Data Rate (Hz)		
FAST	CR23X sn 1036	Tower, 17 m	fast_24.csi	Y	10	Nov 1998 — present	A
PROF	CR23X sn 1037	Tower, 13 m	prf_02.csi	Y	1	Nov 1998 — present	B
MET	CR23X sn 2931	Tower, 11 m	met_10.csi	Y	1	Nov 1998 — present	C
SOIL	CR23X sn 2932	North Canopy Tower, Ground	soil_03.csi	N	5-min avg	Nov 1998 — present	D
CNR	CR23X sn 2089	Tower, 26 m	rad_03.csi	Y	1	Jan 1999 — present	E
UC	CR23X sn 2091	Mini-tower, Ground/Pallet	uc_06.csi	Y	10	Sep 2000 — present	F
TC	CR23X sn 2090	North Canopy Tower, 2 m	tc_13.csi	N	5-min avg	Sep 2001 — present	G
MRS	CR10 sn 18657	North Canopy Tower, 4 m	mrs_03.csi	N	5-min avg	Nov 2001 — present	H
NCARTC	CR23X sn 2403	Tower, 11 m (platform)	nctc_05.csi	Y	1	Sep 2002 — present	I
UCB	CR23X sn 6425	Mini-tower, Ground/Pallet	ucb_17.csi	Y	1	Sep 2005 — present	J
MARK	CR23X sn 2768	Tower, 11 m, (platform)	mark_11.csi	Y	10, 20	Nov 2014 — present	K

A: Primary role: Eddy-covariance flux data from a sonic anemometer (Campbell Scientific, model CSAT3), a closed-path infra-red gas analyzer IRGA (LI-COR, model LI-6262), an open-path IRGA (LI-COR, model LI-7500), a Krypton Hygrometer (Campbell Scientific, model KH2O), thermocouple (type-E), LI-7200 analog CO_2, and EC155 analog CO_2

B: Primary role: Vertical CO_2 profile data from a closed-path IRGA (LI-COR, model LI-6251), valve control and valve-status variable for the LI-6251, precipitation, and air temperature

C: Primary role: Relative humidity, prop-vane winds, barometric pressure, valve control and valve-status variable for the LI-6262; prior to 26 May 2010, the MET data logger had a loose wire in the short-haul modem which caused intermittent periods of 1-Hz data loss

D: Primary role: Soil temperature and moisture data

E: Primary role: Radiation data

F: Primary role: Undercanopy eddy-covariance data (2 CSAT3s and 1 LI-7500)

G: Primary role: Tree bole temperatures

H: Primary role: Vertical snow temperature profile

I: Primary role: Vertical thermocouple temperature profile

J: Primary role: Soil temperature and moisture and undercanopy radiation

K: Primary role: Tree accelerometer data; thermocouples at 10-Hz and 20-Hz

Table 3. The fraction of missing high-rate (10-Hz) data from the FAST CR23X data logger shown by month and year. Months with greater than 20% of high-rate data missing are highlighted in bold. In the two right-hand columns, the total size (in gigabytes) of the raw, high-rate binary data collected for each year and the approximate number of site visits per year, are provided.

Year	Jan 1	Feb 2	Mar 3	Apr 4	May 5	Jun 6	Jul 7	Aug 8	Sep 9	Oct 10	Nov 11	Dec 12	Annual Averages	Total Size (Gb)	No. Site Visits[a]
1998											**0.33**	0	0.165	2.04	
1999	**0.23**	0	0	0.02	0.12	0	**0.27**	0.17	0.11	0.05	0.03	0.04	0.089	18.41	
2000	0.06	0	0.01	0	0	0.02	0.06	0.01	0.04	0	0	0	0.019	27.02	
2001	0	0.01	0.07	0.03	0	0	0.02	0	0	0	0	0.09	0.023	27.78	1
2002	0	0	0.11	0.04	0.12	0.16	**0.23**	0.06	0.08	**0.24**	0.05	0.10	0.100	28.35	6
2003[b]	0.01	0.05	**0.23**	0.14	0.08	0.08	0	0.03	**0.20**	0.04	**0.21**	0	0.090	33.38	79
2004	0	0.02	0.02	0	0.03	0.02	0.02	0.15	0	0.02	0.04	0.04	0.031	35.32	93
2005	0.06	0.05	0	0	0.03	0.03	0.05	0	0	0	0.01	0.05	0.026	34.96	68
2006[c]	0	0	0	0.11	**0.24**	0	0.11	0.01	0.03	0.05	0.03	0	0.052	34.78	68
2007[d]	0.05	0	0.02	0	0.07	0.07	0.01	0.03	0	0	0	**0.32**	0.050	34.76	53
2008	0.08	0	0	0	0.02	0	0	0	0	0	0	0.01	0.015	36.21	41
2009	0	0	0.03	0.10	0.04	0.07	0.03	0.10	0.09	0.03	0	0	0.043	39.08	51
2010	0	0	0	0.02	0.04	0	0	0	0.01	0	0	0	0.009	40.11	40
2011	0	0.11	0	0	0	0	0.01	0	0	0.06	0.09	0	0.022	39.21	33
2012[e]	0	0	0	0	0	0	0.03	0.04	0	0	0	0	0.007	39.15	26
2013[f]	0	0	0	0	0	0	0	0	0.19	0	0	0	0.016	35.58	28
2014	0.03	0	0	0	0	0	0	0	0	0.02	0	0	0.005	44.80	38
2015	0	0	0	0	0.02	0	0	0	0	0	0	0	0.003	72.68	19
	0.033	0.017	0.031	0.028	0.048	0.029	0.051	0.037	0.045	0.033	0.046	0.038	0.036	623.62	644
							Monthly Averages							Cumulative Values	

[a] These are the number of site visit per year by the lead author (SpB) who starting working at US-NR1 in January, 2003

[b] From 18–20 March 2003, a major snowstorm knocked out the power at the US-NR1 site.

[c] From 28 April to 8 May 2006, the power line to the US-NR1 site was compromised.

[d] From 20–29 Dec 2007, russter2 had a hardware failure.

[e] On 12 August 2012, russter2 had a hard drive failure.

[f] From 10-12 September 2013, Boulder County experienced significant rainfall (e.g., Gochis et al., 2014) shutting down power to the site and making access to the site difficult.