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In situ air temperature and humidity measurements over diverse land covers in Greenbelt, Maryland, November 2013–November 2015

Mark L. Carroll[1,2], Molly E. Brown[3], Margaret R. Wooten[1,2], Joel E. Donham[4], Alfred B. Hubbard[1,2], and William B. Ridenhour[5]

[1]Science Systems and Applications Inc, Lanham, MD, USA
[2]NASA-GSFC Biospheric Sciences Lab, Greenbelt, MD, USA
[3]Department of Geographical Sciences, University of Maryland, College Park, MD, USA
[4]NASA-GSFC Medical and Environmental Management Division, Greenbelt, MD, USA
[5]NASA-GSFC Engineering and Construction Branch, Greenbelt, MD, USA

Correspondence to: Mark L. Carroll (mark.carroll@nasa.gov)

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Abstract. As our climate changes through time there is an ever-increasing need to quantify how and where it is changing so that mitigation strategies can be implemented. Urban areas have a disproportionate amount of warming due, in part, to the conductive properties of concrete and asphalt surfaces, surface albedo, heat capacity, lack of water, etc. that make up an urban environment. The NASA Climate Adaptation Science Investigation working group at Goddard Space Flight Center in Greenbelt, MD, conducted a study to collect temperature and humidity data at 15 min intervals from 12 sites at the center. These sites represent the major surface types at the center: asphalt, building roof, grass field, forest, and rain garden. The data show a strong distinction in the thermal properties of these surfaces at the center and the difference between the average values for the center compared to a local meteorological station. The data have been submitted to Oak Ridge National Laboratory Distributed Active Archive Center (ORNL-DAAC) for archival in comma separated value (csv) file format (Carroll et al., 2016) and can be found by following this link: http://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1319.

1 Introduction

While leaders around the world are deliberating about the best ways to slow the rate of climate change through reductions in greenhouse gas emissions, the time to develop and implement adaptation strategies is now. Executive Order (EO) 13693 directs federal agencies to incorporate climate-resilient design and management elements into the operation, repair, and renovation of existing agency buildings and the design of new agency buildings. Climate change in the Washington DC metro area will impact facility operations (e.g., storm-water management, energy supply and demand, cost of utilities), natural resource management (e.g., forest maintenance, invasive species control), mission infrastructure (e.g., labs, testing facilities, and computing capabilities), as well as the quality of life in the community (e.g., drinking water availability, wildfire risk). It is critical to plan for climate change impacts as part of established planning and budgeting cycles within and beyond NASA. US government agencies will need to implement short-term tactical changes while simultaneously planning for longer-term strategic adaptation measures. The Climate Adaptation Science Investigator (CASI) initiative focuses on bringing together NASA scientific expertise with its facilities and environmental planning organizations to ensure that the center develops adaptation strategies for a changing climate.

The CASI working group was formed in 2010 with representatives from each center. The CASI team at Goddard Space Flight Center (GSFC) Greenbelt began working together in the fall of 2011 to discuss and consider problems and solutions for climate change impacts at GSFC-Greenbelt. This team meets monthly to consider how CASI can have a positive impact on the center. After reviewing the information from other CASI workshops, the GSFC-CASI team concluded that there were two aspects of climate change that posed a direct and tangible risk to the ability of the center to meet its mission in the future: the impact of rising temperatures on energy needs and the potential increase in frequency of high-intensity rainfall events. We held a two-day workshop to address these concerns with internal stakeholders at the GSFC Greenbelt campus. The primary goal of the workshop was to identify a path forward that would integrate climate change considerations in the center Facilities Master Plan.

Based on climate predictions from NASA Goddard Institute for Space Studies (GISS), it is likely that GSFC-Greenbelt will experience increased temperatures and intensifying rainfall events. These two stresses will exacerbate problems with energy sustainability and with storm-water management (Table 1).

While the impacts of atmospheric climate change have been the subject of significant research, urban heat island (UHI) effects have also been demonstrated to be equal in magnitude to climate change effects. The GSFC-CASI team performed a study to collect data to evaluate the contribution of various land cover types at the GSFC facility at the microclimate scale.

An urban heat island occurs when dense concentrations of built surfaces retain heat differently than their suburban or rural surroundings. Numerous studies have investigated this phenomenon on large cities using satellite data and models (Chun and Guldmann, 2014; Sun and Augenbroe, 2014; Zhang et al., 2012). However these studies yield little information to support specific interventions on the local scale that would reduce urban heating. To improve understanding of urban heating, microclimate and potential mitigation strategies on the campus scale, we deployed and monitored 12 environmental monitoring sensors (temperature and relative humidity) on 5 different surface types around the center. This study served as a bridging activity between the other GSFC-CASI activities related to building energy management analysis and the storm-water hydrological analysis. The goals of this study were to collect temperature and humidity data for a minimum of 1 year and have duplicate measurements over representative surface types at the center.

2 Study site and equipment

NASA Goddard Space Flight Center is a controlled-access facility (i.e., requires a badge to enter) located in the heavily developed suburbs of Washington, DC in Greenbelt, MD. It is a mixed-use area with retail and commercial office space intermixed with residential area – both high-density and single-family homes (Fig. 1). The center itself is comprised of approximately 526 ha with 5 main land cover types: urban/building, urban/road, forest, grass/field, and wetland. The National Land Cover Database (NLCD) was used for land cover analysis (Homer et al., 2015) to give a sense of the relative distribution of different land cover types at the center. This dataset is designed to provide decadal land cover data for the conterminous United States. It is primarily based on decision-tree classification of Landsat data and is available at 30 m spatial resolution. In this study, the NLCD 2011 was downloaded and cropped to GSFC using property boundary shapefiles provided by the GSFC facilities management division. The area of each significant ($\geq 5\,\%$ of total area) land cover class represented at GSFC is displayed in Table 2, and the relative areas of each significant class are displayed in a pie chart in Fig. 2.

For this study we purchased 12 "HOBO U23 Pro v2 External Temperature/Relative Humidity Data Loggers – U23-002" to record data at the center. The loggers were programmed to record temperature and humidity at 15 min intervals beginning at the start of an hour. In this way all loggers were recording at the same time. The loggers were mounted on posts at 2 m height above the ground with the actual logger mounted inside a radiation shield to minimize direct sunlight on the probe (Fig. 3). The 12 loggers were deployed on 5 different surface types (Fig. 1) around the center: asphalt parking lot, bright surface roof, grass field, forest, and storm-water mitigation feature.

2.1 Logger placement

Loggers were placed in pairs on each surface to be tested to minimize concerns about discrepancies in measurements between any two individual loggers where possible. In the cases of the forest and storm-water management structures, loggers were placed in example locations rather than close proximity pairs to cover the range of conditions. A detailed log of dates and duration of events during the deployment of the loggers was kept throughout the project and is shown in Table 3. The surface types where the loggers were placed have been described in terms of their physical location and parenthetically in terms of the "local climate zone" (Stewart and Oke, 2012). Loggers were placed in best available locations to minimize the disturbance of the sensors and to represent the surface types that are typical of the GSFC-Greenbelt campus. Criteria used for site selection included accessibility for data download and sensor maintenance, minimal amount of human and/or vehicle traffic, and representativeness of the surface type at the center.

2.2 Grass field (local climate zone – D "low plants")

A grass field adjacent to building 6 was used to represent the areas of maintained vegetated area. Grass in this field was routinely mowed in the spring and summer. Weed trimmers were used to keep grass from growing around loggers.

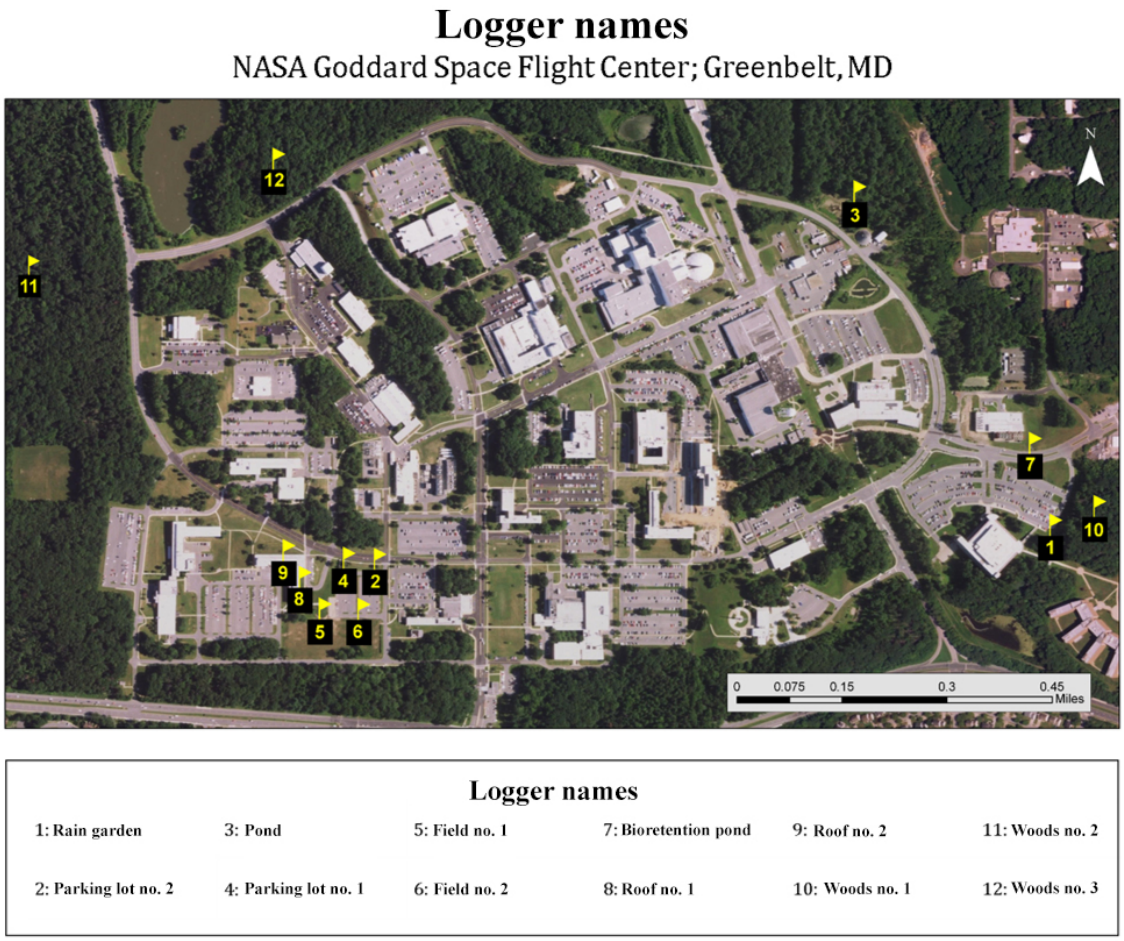

Figure 1. Map of Goddard Space Flight Center. Flags indicate locations of loggers at the center. Loggers were strategically placed in low-traffic areas of the center to minimize the potential for disturbance.

Table 1. Qualitative changes in extreme events for GSFC based on global climate model simulations, published literature, and expert judgment. Source: NASA GISS likelihood definitions based on IPCC: > 90 % very likely, > 66 % likely, > 50 % more likely than not, 33 to 66 % about as likely as not (Rosenzweig et al., 2014).

Event	Direction of change	Likelihood
Heat stress	Increase	Very likely
Ice storms/freezing rain	Increase	About as likely as not
Snowfall frequency and amount	Decrease	Likely
Intense precipitation events	Increase	Likely
Drought	Increase	More likely than not

Two loggers (loggers 5 and 6) were placed approximately 2 m apart in this location (Fig. 3a). Both loggers were a minimum of 10 m from adjacent land cover types (i.e., building, parking lot and trees). The loggers were placed such that no shadows from structures or trees were cast on the loggers during any season, which minimized the potential impact on temperatures caused by simple shadowing.

2.3 Bioremediation structures (local climate zone – C "bush, scrub")

Three loggers were placed in or adjacent to three distinct bioremediation structures. Bioremediation structures are defined here as shrub-dominated and small-tree-dominated rain gardens and a small storm-water retention pond. Two rain gardens adjacent to parking lot for building 32 were selected to help quantify the localized effect of the rain gar-

Table 2. Total area of each land cover type for GSFC as determined by the NLCD and related to the local climate zone (LCZ) of Stewart and Oke (2012).

National Land Cover Dataset class	Local climate zone	Logger number	Area (ha)
Developed open space	LCZ – D	5, 6	74.52
Developed low intensity	LCZ – B	1, 3, 4	62.79
Developed medium intensity	LCZ – 5		52.65
Developed high intensity	LCZ – 5, E	2, 4, 8, 9	27.9
Deciduous forest	LCZ – A	12	140.22
Evergreen forest	LCZ – A	11	55.98
Mixed forest	LCZ – A	10	64.17
Other	LCZ – 9		45.81

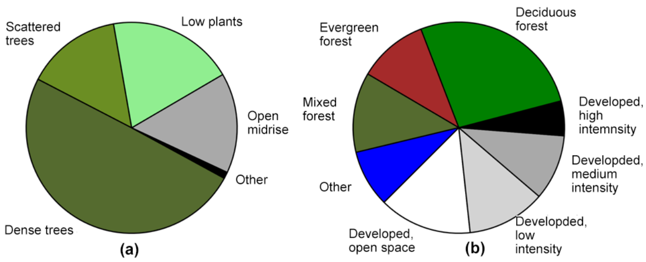

Figure 2. Distribution of land cover types at Goddard Space Flight Center. **(a)** Amount of area as determined by Stewart and Oke local climate zones; **(b)** amount of area as determined by the National Land Cover Dataset (NLCD).

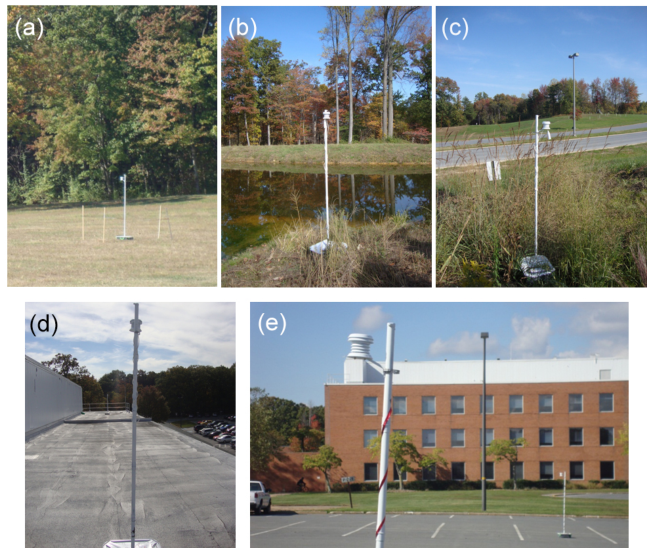

Figure 3. Photo montage of loggers installed at NASA GSFC. **(a)** Logger 5 installed in the field next to building 6; **(b)** logger 3 installed next to the pond; **(c)** logger 7 installed in rain garden adjacent to parking lot for building 32; **(d)** loggers 8 and 9 installed on the roof of building 6; **(e)** loggers 2 and 4 installed in the parking lot adjacent to building 6, which can be seen in the background.

den specifically on humidity. In the rain gardens the loggers (loggers 1 and 7) were placed approximately 2 m from the adjacent parking lot (Fig. 3c). The parking lot receives heavy daily use with passenger vehicles. Logger 1 was also approximately 2 m from an adjacent forest patch that provided a small amount of shade to the logger primarily in the mornings in the spring/summer (during "leaf-on" season for deciduous trees). Logger 3 was placed adjacent to a small (< 1 acre) storm water retention pond (Fig. 3b). During winter and spring the water in the pond surrounded the base of the logger with a maximum water depth of < 0.2 m. Water was present in the pond continuously throughout the entire study period and was frozen with surface ice for short periods during winter months. All three of these sites were selected at the request of the facilities management division, an active partner in this project.

2.4 Rooftop (local climate zone – 5 ("open midrise")

Two data loggers (loggers 8 and 9) were placed on the roof of building 6. This building is typical of the buildings at GSFC: 3 – story steel and concrete construction, red brick facade, low-albedo painted roof material. Loggers were placed at least 3 m from the edge of the roof, at least 10 m from any heating ventilation and air conditioning (HVAC) exhaust vents, and placed approximately 15 m apart from each other (Fig. 3d). Total height of the building is approximately 14 m. The roof of this building has no other equipment on it and is a limited access area. Loggers were placed on the south side of the building away from trees and other obstructions.

2.5 Parking lot (local climate zone – E "bare rock or paved")

The parking lot adjacent to building 6 is asphalt construction with spaces defined by white painted lines and unpainted concrete curbs. The asphalt is untreated (i.e., no blacktop sealant) yielding a medium-albedo surface (Fig. 3e). This parking lot was selected as a low-use area with minimum impact to users of the building and minimum impact to the

Table 3. Log of events recorded during the study period. Date format is month/day/year.

Date	Time	Offload?	Action	Comments
10/31/2013		X	Collection 01: 10/28/13–10/31/13	
11/14/2013	12:51		Loggers 2 and 4 moved to field	
11/19/2013	09:15		Loggers 2 and 4 moved back to lot	
11/19/2013		X	Collection 02: 10/31/13–11/19/13	
12/04/21013		X	Collection 03: 11/19/13–12/04/13	
12/18/2013		X	Collection 04: 12/04/13–12/18/13	
1/2/2014	16:18		Loggers 2 and 4 moved to field	
1/6/2014	08:28		Loggers 2 and 4 moved back to lot	
1/15/2014		X	Collection 05: 12/18–1/15	
12/18/2013–01/03/2014			missing data	
1/20/2014	18:52–18:54		Loggers 2 and 4 moved to field	
1/27/2014	14:54		Loggers 2 and 4 moved back to lot	
1/30/2014	10:32		Relaunched shuttle	
1/30/2014		X	Collection 06: 01/15/14–01/30/14	
2/12/2014	16:35		Loggers 2 and 4 moved to field	
2/18/2014	13:00		Loggers 2 and 4 moved back to lot (not yet in correct spot)	
2/18/2014	13:30		Loggers 2 and 4 moved to spots in lot	
2/18/2014			Logger 2 surrounded by ice until 2/19?	
2/20/2014			Logger 3 (salt dome pond) observed being frozen over	
2/20/2014		X	Collection 07: 01/30/14–02/20/14	
2/24/2014	09:03–09:27		Logger 2 out of commission (Joel fixed tilt)	
3/2/2014	12:00		Loggers 2 and 4 moved to field	
3/4/2014	11:30		Loggers 2 and 4 moved back to lot	
3/12/2014	14:45–14:50		Logger 3 down (Joel restood)	
3/14/2014		X	Collection 08: 02/20/14–03/14/14	
4/2/2014			Logger 9 observed missing shield	
4/2/2014		X	Collection 09: 03/14/14–04/02/14	
4/23/2014		X	Collection 10: 04/02/14–04/23/14	
5/1/2014	11:22–11:26		Replaced shield on Logger 9	
5/15/2014		X	Collection 11: 04/23/14–05/15/14	
6/18/2014		X	Collection 12: 05/15/14–06/08/14	
6/18/2014			USB to shuttle broke off, sent to HOBO for repair	
7/22/2014		X	Collection 13: 06/18/14–07/22/14	
8/27/2014		X	Collection 14: 07/22/14–08/27/14	
10/1/2014		X	Collection 15: 08/27/14–10/01/14	
11/6/2014		X	Collection 16: 10/01/14–11/06/14	
12/8/2014	13:45–15:25		Joel drilled holes in bases (drainage) and secured solar shields	
12/10/2014		X	Collection 17: 11/06/14–12/10/14	
1/13/2015	09:18		Loggers 2 and 4 moved to field (construction)	
1/15/2015		X	Collection 18: 12/10/14–01/15/15	
1/15/2015			Noticed pond frozen, probably been so for a few weeks	

Table 3. Continued.

Date	Time	Offload?	Action	Comments
1/21/2015			Snowfall beginning around 12:15	
1/22/2015	11:40		Loggers 2 and 4 moved back to lot, but switched locations	Loggers 2 and 4 remained switched for the remainder of data record
2/25/2015		X	Collection 19: 01/15/15–02/25/15	
4/7/2015		X	Collection 20: 02/25/15–04/07/15	Logger 6 for collection20: no data (data were corrupt)
5/26/2015		X	Collection 21: 04/07/15–05/26/15	
5/28/2015	13:23		Loggers 5 and 6 moved from field	
5/28/2015	14:00		Loggers 5 and 6 moved to field by Goddard Day Care temporarily	
7/1/2015		X	Collection 22: 05/26/15–07/01/15	
8/6/2015	14:25–14:35		Logger 6 moved back to field	
8/6/2015		X	Collection 23: 07/01/15–08/06/15	
9/2/2015		X	Collection 24: 08/06/15–09/02/15	
9/3/2015	09:00–09:20		Logger 5 moved back to field	
9/8/2015	12:23–12:28		Loggers 2 and 4 moved to lot parking between B6 and B11	
10/20/2015		X	Collection 25: 09/02/15–10/20/15	
11/19/2015		X	Collection 26: 10/20/15–11/19/15	

loggers due to vehicle traffic/parking in the lot. Two loggers (loggers 2 and 4) were placed in the center of adjacent parking spaces approximately 2 m apart with four parking spaces coned off to limit the potential impact of cars parking next to the sensors. These loggers were moved several times in the winter to allow for snow removal and were returned to their same locations after the snow event concluded. The dates and duration of these moves are indicated in the log shown in Table 3.

2.6 Forest (local climate zone – A "dense trees")

Three loggers were placed in three distinct forest areas around GSFC. In all cases the loggers were placed a minimum of 20 m from any adjacent land cover type (e.g., road, field, parking lot). Care was taken to ensure that loggers were not placed in obvious "gaps" in the forest so that the measurements would be representative of the cover type. Logger 10 was placed in a mixed forest patch (∼ 3.24 ha), logger 11 was placed in an evergreen dominated forest patch (∼ 37.23 ha), and logger 12 was placed in a deciduous forest patch (∼ 124.64 ha).

3 Data

The loggers were initialized in the office in September 2013. They were placed in a box with ventilation for 2 weeks on a shelf in the office to assess the amount of agreement between the loggers in a controlled environment. The box was moved to a garage with no temperature controls for an additional 2 weeks prior to being deployed in the field in late October 2013. Data were downloaded every 2–3 weeks. A portable data shuttle was used to download data in the field and transfer it to a PC, and a log of observations and dates of download was maintained (Table 3). The loggers were retrieved in November 2015 after collecting data for 2 years continuously. Upon retrieval the loggers were placed in a box and stored in the same garage as prior to being deployed for 2 weeks. The box was moved to the climate-controlled office for 2 more weeks after which data collection stopped. The information collecting during the pre- and post-deployment can be used to determine sensor-to-sensor agreement both before deployment and after retrieval. This will allow a user to assess the impact of 2 years in the field on sensor agreement and to put appropriate error bars on the analysis of the data.

Direct logger data are stored in proprietary file format with one file per logger per download. These data were converted to Microsoft Excel file format and compiled to a single data file with all 12 loggers and all dates for ease of use. The data are stored in five files, one for each significant period of collection: office pre-calibration, garage pre-calibration, live data collection, garage post-calibration, and office post-calibration.

The full log of events is in the Table 3, but several notable events during the data collection are listed here:

- Data gap for all loggers occurred in January 2014 due to failure of data retrieval device.

- Data gap for logger 6 occurred in April 2015.

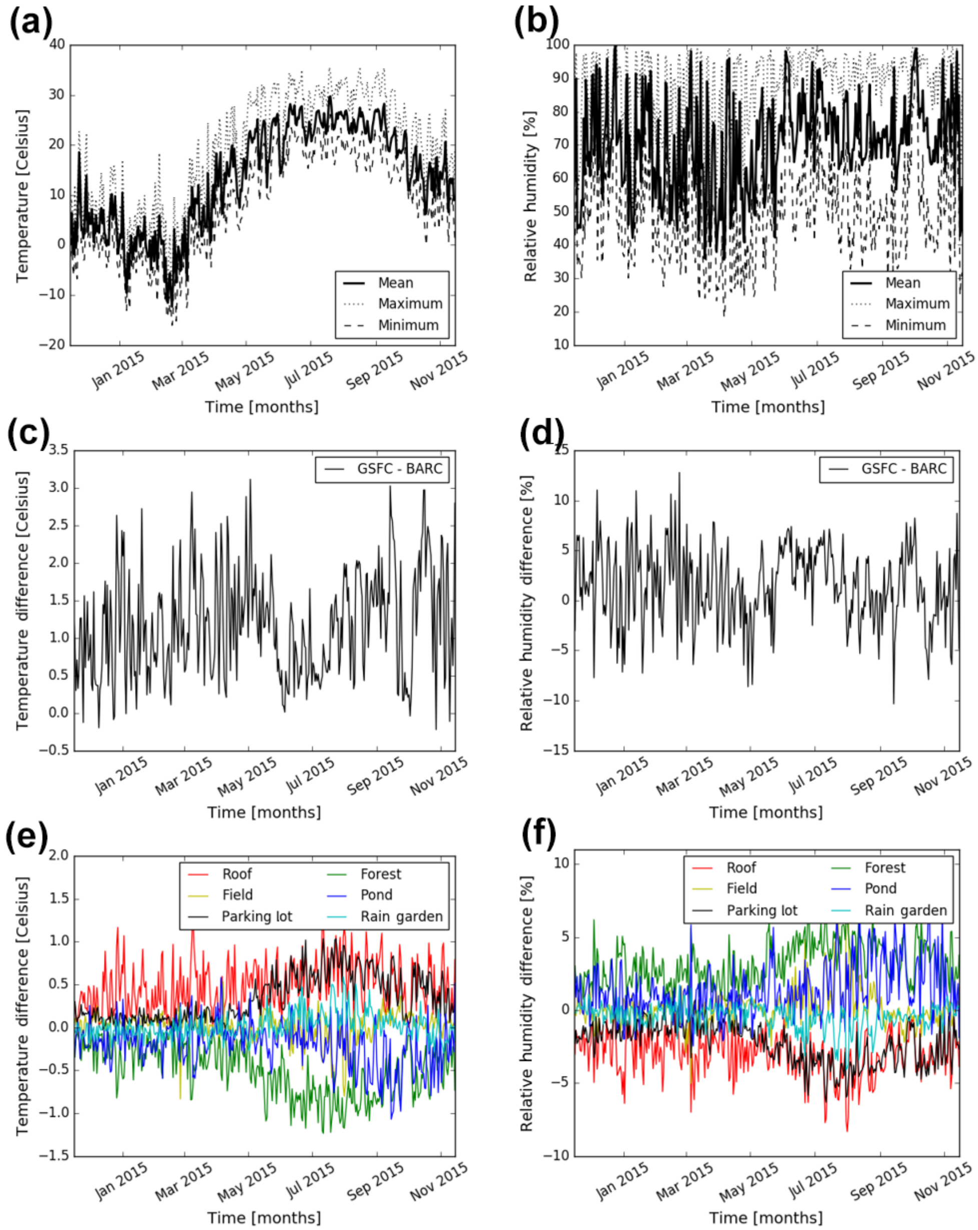

Figure 4. Plot of logger data for year 2 of data collection from November 2014 to November 2015. Figures in the left column show temperature features in degrees Celsius while figures on the right show relative humidity in percent.

- Parking lot loggers were moved several times for safety during winter storm events.
- Field loggers moved due to special event.
- Effort was made to find a suitable alternate location during each event.

Weather data

Beltsville Agricultural Research Center (BARC) maintains seven meteorological stations. For this analysis data from the closest of these – station 3 (approximately 4 km from GSFC) – were used (http://www.ba.ars.usda.gov/weather/ba-weather). The station 3 is located in an agricultural setting surrounded by large tracts of contiguous forest bisected by rural and highway roads. These data are collected at 15 min intervals with daily summary statistics available from the BARC data portal. Daily mean values were downloaded for the time period of the GSFC dataset and used for comparison.

There are several National Weather Service (NWS) weather stations nearby that were not chosen for this study because they do not have humidity data available. The BARC stations were the only available data with public access and the availability of humidity data. The BARC data serve the general purpose of this paper – which is to show that the data collected at GSFC are in agreement with local established weather station data.

4 Results and discussion

GSFC-Greenbelt is a controlled-access facility, which means that admission is granted for official business only and is not open to the general public. This creates an ideal environment to take long running measurements on various surface types with minimal concern for vandalism and unintended interference from the general population. If a similar network was deployed in a typical urban environment the loggers could be exposed to more human interaction and generally a greater level of activity from vehicle and pedestrian traffic.

The period during which the data were collected was ideal for capturing a wide range of temperature conditions. The east coast experienced record cold as well as very warm conditions during 2014 (Trenary et al., 2015). Summer temperatures in 2015 were the hottest on record, although the weather in the Greenbelt area was only slightly above average.

Three diagnostic plots were generated to display the characteristics of the temperature and relative humidity data collected from the loggers. These plots represent (1) relative difference between GSFC and a local meteorological station; (2) relative difference between the loggers based on land cover type; and (3) the minimum, maximum, and mean values for the center regardless of surface type.

The loggers were programmed to record data at 15 min intervals. To analyze the data, the mean, maximum, and minimum were calculated individually for each logger. The results for all 12 loggers were then averaged to generate one set of summary data for GSFC. These are displayed in Fig. 4a–b for the second year of data collection, and the mean values served as the GSFC data for Fig. 4c–d. The other data used for Fig. 4c–d were from a local meteorological dataset, collected at the BARC and described earlier in the data section of this paper. The difference between the average daily mean values for all of GSFC and the daily mean values for BARC was calculated, and the results are shown in Fig. 4c–d for the second year of GSFC data collection. These plots show only the second year to improve readability, but it should be noted that the first year contains a data gap of approximately one month in length that is therefore not displayed. Finally, as described above, loggers were deployed to get measurements over each distinct land cover type represented at the center. The daily means were averaged together according to land cover, meaning that each value is the average of the daily mean values for all of the loggers deployed in that land cover type. The difference between this land cover average and the average value for all of the GSFC loggers was then calculated, and these results are displayed in Fig. 4e–f for the second year of GSFC data collection.

5 Conclusions

The loggers were deployed for two full years, though some small data gaps do exist. The data collected describe the microclimate of five different surface types in a campus setting at Goddard Space Flight Center in Greenbelt, MD. A brief analysis of the data shows trends similar to a local weather station for both parameters that were measured: temperature and humidity. The data show differences in microclimate between different land cover types at the center and are suitable for use as a validation dataset for a satellite-based study. This could be used as a stand-alone study of the impact of surface type on heating in a campus setting, and it could be used internally by GSFC facilities to evaluate the impact of localized heating on building energy usage.

6 Data availability

The 15 min logger data (Carroll et al., 2016) is available through the Oak Ridge National Laboratory DAAC. The meteorology data is available from the Beltsville Agricultural Research Center http://www.ba.ars.usda.gov/weather/ba-weather-3.html.

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