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Meteorological Data for Selected Sites along the Colorado River Corridor, Arizona, 2011–13

Open-File Report 2014–1247

U.S. Department of the Interior
U.S. Geological Survey

Cover: Southern view from a monitoring station in Furnace Flats, Grand Canyon National Park, Arizona. Photograph by Joshua Caster, U.S. Geological Survey Grand Canyon Monitoring and Research Center.

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
inch of mercury at 32ºF (in Hg)	33.8638867	millibars (mbar)
mile (mi)	1.609	kilometer (km)
mile per hour (mi/h)	0.44704	meter per second (m/s)

SI to Inch/Pound

Multiply	By	To obtain
millimeter (mm)	0.03937	inch (in.)
meter per second (m/s)	3.281	foot per second (ft/s)
millibars (mbar)	0.02953	inch of mercury at 32ºF (in Hg)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F = (1.8 × °C) + 32.

Meteorological Data for Selected Sites along the Colorado River Corridor, Arizona, 2011–13

By Joshua Caster, Timothy Dealy, Timothy Andrews, Helen Fairley, Amy Draut, Joel Sankey, and David Bedford

Abstract

This report presents data from 14 automated weather stations collected as part of an ongoing monitoring program within the Grand Canyon National Park and Glen Canyon Recreation Area along the Colorado River Corridor in Arizona. Weather data presented in this document include precipitation, wind speed, maximum wind gusts, wind direction, barometric pressure, relative humidity, and air temperature collected by the Grand Canyon Monitoring and Research Center at 4-minute intervals between January 1, 2011, and December 31, 2013, using automated weather stations consisting of a data logger and a weather transmitter equipped with a piezoelectric sensor, ultrasonic transducers, and capacitive thermal and pressure sensors. Data collection was discontinuous because of station additions, station removals, changes in permits, and equipment failure. A large volume of data was collected for each station. These data are part of a larger research effort focused on physical processes affecting landscapes and archaeological-site stability in the Colorado River Corridor—both natural processes (including meteorological events) and those related to the Glen Canyon Dam operations. Meteorological conditions during the study interval were warmer and drier than is typical, due to ongoing drought conditions during the time period studied. The El Niño/Southern Oscillation was primarily in a neutral state during the reporting period.

Introduction and Purpose

The Colorado River within the Grand Canyon National Park, Arizona, has been regulated since construction of the Glen Canyon Dam in 1963. To assess potential impacts on downstream cultural, environmental, and recreational resources caused by changes in the river flow regime and sediment supply, the Bureau of Reclamation (Reclamation) initiated the Glen Canyon Dam Adaptive Management Program (U.S. Department of the Interior, 1995). As part of this initiative, the U.S. Geological Survey (USGS) Grand Canyon Monitoring and Research Center (GCMRC) and its cooperators monitor the effects of dam operations.

Monitoring efforts by the GCMRC have focused on a variety of parameters to assess downstream effects of Glen Canyon Dam. In 2003, meteorological data collection began as part of a study to relate geomorphic changes to meteorological events at and upslope of the active channel within the Colorado River Corridor. The weather data described here, and those collected previously, are part of a larger research effort focused on physical processes affecting archaeological-site stability in the Colorado River corridor—both natural processes (including meteorological events) and those related to dam operations. This research effort involves assessing relations between physical landscape processes, including meteorological events, and the physical integrity of archaeological sites. Measuring meteorological conditions and, in a separate but related effort, measuring sediment erosion and deposition in selected areas of the river-corridor landscape, allows researchers to identify natural and dam-induced changes to the river corridor. Meteorological data will be used in this larger research effort to evaluate the potential restorative effects of high-flow releases from the Glen Canyon Dam, including the monitoring of windblown sand supply from new river sandbars toward upland archaeological sites (Draut and Rubin, 2008; Draut and others, 2010a; Draut, 2012), precipitation-induced erosion (Collins and others, in press), gullying, and gully annealing by windblown sediment (Sankey and Draut, 2014).

Weather data collection between 2003 and 2006 used spinning-cup anemometers and tipping-bucket rain gages with an automated data logger to measure 4-minute wind direction, wind speed, maximum wind gusts, and precipitation at nine locations within the Grand Canyon, Arizona (Draut and Rubin, 2005; Draut and Rubin, 2006). The 4-minute time interval for data collection was selected as it provided the highest resolution information that would not exceed the data logger storage capacity between scheduled data collection operations.

Beginning in February 2007, GCMRC installed 11 new weather stations at 9 sites within the Colorado River Corridor; 4 of the station locations were used during the previous study by Draut and others (2009a). These weather stations consisted of a data logger and an automated weather transmitter with a piezoelectric sensor, ultrasonic transducers, and capacitive thermal and pressure sensors to collect multiple weather parameters (wind direction, wind speed, maximum wind gusts, precipitation, temperature, barometric pressure, and relative humidity) at 4-minute intervals without moving parts. Data collected from these 9 weather monitoring sites for 2007, 2008, 2009, and 2010 have been presented in previous reports by Draut and others (2009, 2009b, 2010b) and Dealy and others(2014). Following a hiatus in data collection, 8 of the 11 stations were removed in 2012. The three remaining stations (AZ C:05:0031 Upper, AZ C:13:0346 Upper, AZ G:03:0072) as well as three new stations (AZ C:02:0071, AZ C:02:070, AZ B:10:0225) were activated in spring 2013 and are still operating as of spring 2014.

The purpose of this report is to present data collected by GCMRC weather stations between January 1, 2011, and December 31, 2013, and to establish a process for reporting future weather data. Weather parameters during this period were collected from the 11 automated stations that were used for previous reports by Draut and others (2009a, 2009b, 2010b, and Dealy and others, 2014) that were in operation through fall 2011, three of which were reactivated in 2013, and three additional automated weather stations deployed in 2013 at sites AZ C:02:0071, AZ C:02:070, and AZ B:10:0225 (fig. 1). Reported meteorological data from these 14 automated weather stations were wind direction, wind speed, maximum wind gusts, air temperature, barometric pressure, relative humidity, and rainfall. Records from all 14 stations are fragmentary because of station removal, staggered station installation, equipment malfunction, and monitoring permit modification. Explanations of gaps within the data collected from the automated weather stations are included in this report and a detailed list is provided in appendix 1.

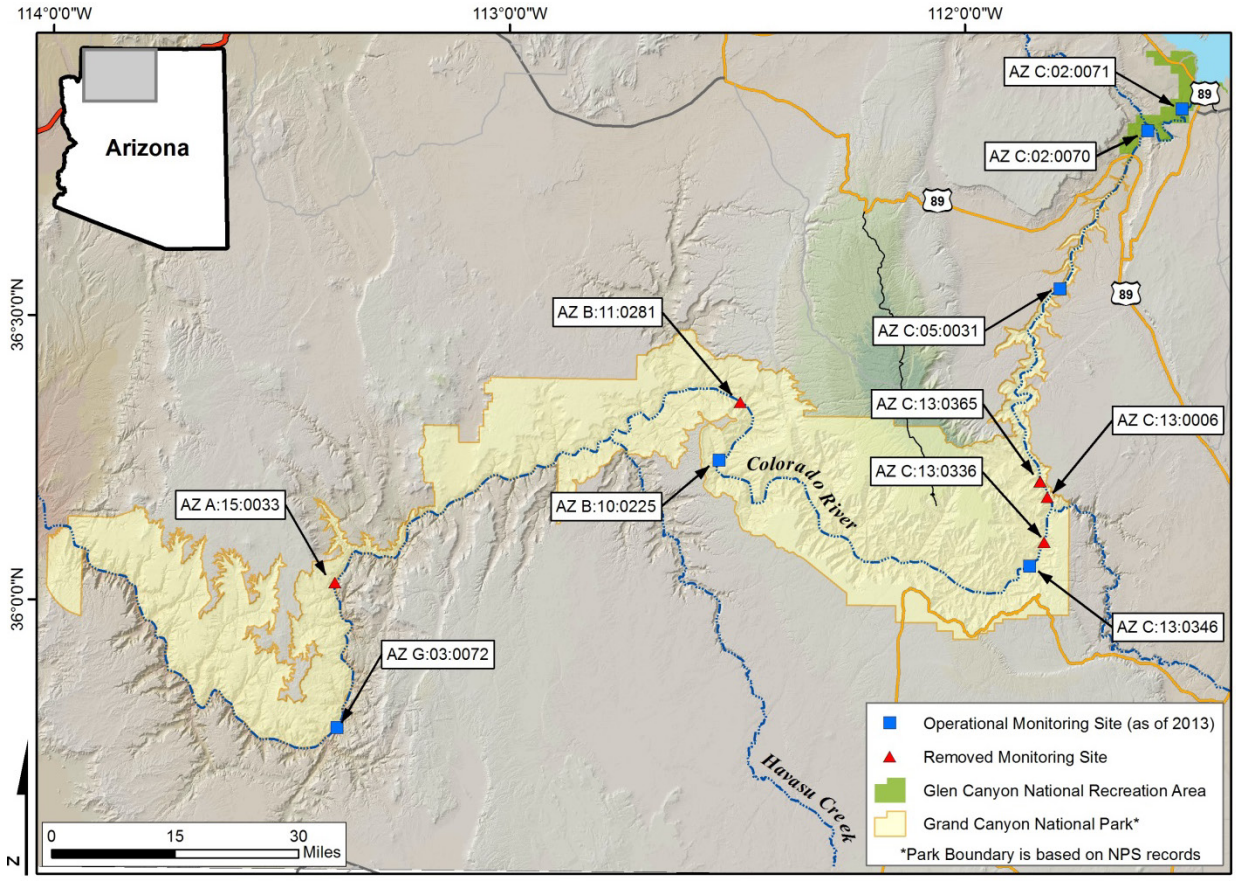

Figure 1. Map showing locations of weather monitoring sites the Colorado River Corridor through Glen and Grand Canyons, Arizona. There are 14 automated weather stations within 11 monitoring sites. Sites AZ C:05:0031, AZ C:13:0365, and AZ C:13:0346 contained two stations prior to 2012. After summer 2011, all operational monitoring sites contained only one station.

Monitoring Locations and Period of Observation

GCMRC monitored 14 automated weather stations at 11 monitoring sites for at least a portion of the reporting period from January 2011 to December 2013. Site locations were selected based on the potential for gully erosion and aeolian influx of fluvial sand deposited upwind of the site along flood shorelines (Draut and Rubin, 2005). These weather monitoring sites were distributed along approximately 230 river miles of the Colorado River corridor within the Grand Canyon National Park and the Glen Canyon Recreation Area. Distances between monitoring sites ranged from 2 to 68 river miles. Three of these monitoring sites contained two weather stations for the purpose of assessing intra-site variability and quality control of readings. Monitoring sites have been designated with a 7-digit alpha-numeric code corresponding to previous reports (Draut and others, 2009a, 2009b, 2010b). Where two stations were present at a monitoring site, a qualifier of *Upper*, for the upstream station in respect to the Colorado River, or *Lower*, for the downstream station, was added to the designation.

None of the 14 automated weather stations collected data for the entire reporting period from January 1, 2011, through December 31, 2013. Data collection for all sites ceased between November 22, 2011, and April 27, 2013, following a transitional period between the National Park Service research and monitoring permits. After the issuance of the 2013 permit, only three of the automated weather stations deployed in 2007 were re-activated (AZ C:05:0031Upper, AZ C:13:0346 Upper, AZ G:03:0072), and three new stations (AZ C:02:0071, AZ C:02:070, AZ B:10:0225) were installed. Four of the six stations in operation during 2013 retained a continuous record between installation and the end of the reporting period. Data collection was disrupted for sites AZ B:10:0225 and AZ G:03:0072 because of power loss and station removal, respectively. A summary of station names, locations, and operational periods is presented in table 1 and a comprehensive list of gaps within the data is provided in appendix 1.

Table 1. Description of weather monitoring sites and stations, Colorado River Corridor, Grand Canyon, Arizona, 2011–13.

[Stations are listed in order from upstream (in respect to the Colorado River) to downstream]

Monitoring site	Monitoring station	7.5 minute quadrangle	Geographic description	Topographic description	Operational period
AZ C:02:0071	AZ C:02:0071	Ferry Swale	Near the confluence of Ferry Swale Canyon and the Colorado River.	Within a shallow depression on a point bar.	Nov 5, 2013 to Dec 31, 2013
AZ C:02:0070	AZ C:02:0070	Lees Ferry	Near the confluence of the Paria and the Colorado Rivers.	On a cobble bar.	Jun 12, 2013 to Dec 31, 2013
AZ C:05:0031	AZ C:05:0031 Upper	North Canyon Point	Near the confluence of Sheep Spring Wash and the Colorado River.	On the proximal portion of a debris fan.	Jan 1, 2011 to Jul 28, 2011 Apr 27, 2013 to Dec 29, 2013
	AZ C:05:0031 Lower				Jan 1, 2011 to Jul 28, 2011
AZ C:13:0365	AZ C:13:0365 Upper	Cape Solitude	Near the confluence of Malgosa Creek and the Colorado River.	Along a minor distributary of Malgosa Creek.	Jan 1, 2011 to Jul 31, 2011
	AZ C:13:0365 Lower				Jan 1, 2011 to Jul 31, 2011
AZ C:13:0006	AZ C:13:0006	Cape Solitude	Near the confluence of Sixtymile Creek and the Colorado River.	On the proximal portion of a debris fan.	Jan 1, 2011 to Jun 22, 2011
AZ C:13:0336	AZ C:13:0336	Cape Solitude	Near the confluence of Palisades Creek and the Colorado River.	On the proximal portion of a reattachment bar.	Jan 1, 2011 to Aug 2, 2011
AZ C:13:0346	AZ C:13:0346 Upper	Desert View	Near the confluence of Basalt Creek and the Colorado River	On a terrace in a largely inactive aeolian dune field.	Jan 1, 2011 to Aug 2, 2011 May 2, 2013 to Dec 31, 2013
	AZ C:13:0346 Lower				Jan 1, 2011 to Nov 22, 2011
AZ B:10:0225	AZ B:10:0225	Fossil Bay	Near the confluence of Fossil Canyon and the Colorado River.	On the proximal portion of a debris fan.	May 6, 2013 to Nov 1, 2013
AZ B:11:0281	AZ B:11:0281	Tapeats Amphitheater	Near the confluence of Bonita Creek and the Colorado River.	On the medial portion of a debris fan.	Jan 1, 2011 to Feb 27, 2011
AZ A:15:0033	AZ A:15:0033	Whitmore Point SE	Near the confluence of Spring Canyon and the Colorado River.	On the medial portion of a reattachment bar.	Jan 1, 2011 to Aug 6, 2011
AZ G:03:0072	AZ G:03:0072	Diamond Peak	Near the confluence of Two Hundred and Twentyfour Mile Canyon and the Colorado River.	On the medial portion of a debris fan.	Jan 1, 2011 to Aug 11, 2011 May 11, 2013 to Jul 5, 2013

Materials and Methods

Data collection was conducted using automated weather stations. Each station (fig. 2) consists of a transmitter and data logger mounted on a tripod and powered by a 12-volt deep cycle 55-amp-hour AGM Optima battery (model D34/78) enclosed in a plastic box at the base of the tripod. The battery is charged by a 30 watt BP Solar multicrystalline photovoltaic module (BP SX30U). The solar module is mounted to the tripod with an Ameresco Solar's HPM18-30U horizontal pole mount system and is regulated by Morningstar Corporation's SunKeeper™ 6-amp 12 VDC solar charge controller.

The transmitters used for each station are Vaisala™ type WXT510 or WXT520 that measure air temperature, barometric pressure, precipitation, relative humidity, wind speed, and wind direction. The Vaisala™ WXT510/520 transmitter was selected because it could collect multiple parameters without moving parts that reduce visibility to canyon visitors and because of the potential for equipment malfunction associated with moving parts in a desert environment, such as interference from windblown sand.

Data are collected from the Vaisala™ transmitter using a NexSens™ Technology data logger. The NexSens Technology, Incorporated Intelligent Sensor Interface and Control (iSIC) data logger is a 2-megabyte remote data acquisition system that is housed in a weather-proof fiberglass enclosure and has an operating temperature range of -20 to 60 °C.

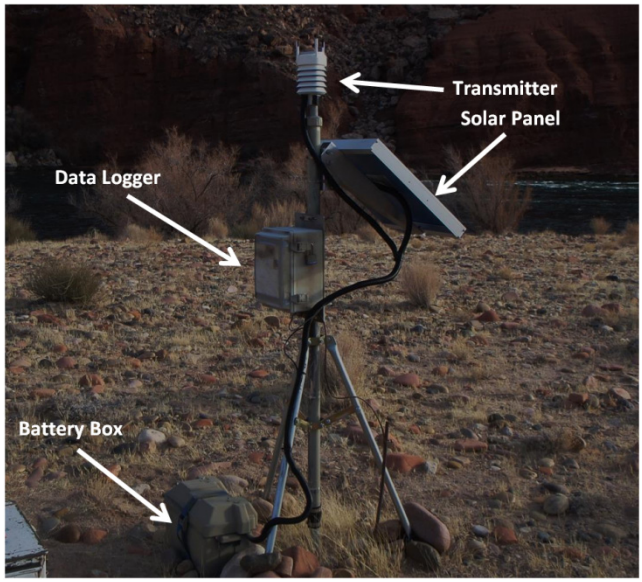

Figure 2. Photograph showing automated weather station. Photograph by Joshua Caster, U.S. Geological Survey.

Each transmitter station is mounted on a tripod assembly made from a Ronard Industries, Inc. extra heavy duty tripod that was used to hold an electric metallic tube (EMT) conduit mast in place. The mast is attached with a Fernco coupler to a length of EMT that is driven between 0.5 and 1 m into the ground. The tripod and mast assembly is adjusted so that the transmitter is 2 m above ground. The transmitter is then oriented to true north based on magnetic declination collected from the National Oceanic and Atmospheric Administration's (NOAA) National Geophysical Data Center's Magnetic Field Calculator using the World Magnetic Model (Maus and others, 2010).

The NexSens^{TM} Technology, Inc. data loggers are programmed to collect data at 4-minute intervals until the maximum data storage capacity has been reached. The data loggers have potential to exceed maximum storage capacity after 5 months of continuous data collection for weather parameters at 4-minute intervals. To avoid loss, data are downloaded from the stations at least once every 4 months. Data are retrieved by directly connecting a field computer to the data logger using an analog cable.

Meteorological Parameters

Seven meteorological parameters are collected at each automated weather station at 4-minute intervals. Wind parameters are collected by the Vaisala^{TM} transmitter using three top-mounted ultrasonic transducers. Based on an assessment of ultrasonic wind readings by Wauben (2005), ultrasonic transducers have the potential to overestimate wind gusts when compared to cup anemometers. Wauben (2005) concluded that the Vaisala^{TM} system was comparable with the conventional cup anemometer and vane system in wind speed and vector during field and wind tunnel tests, although wind speeds less than 5 m/s showed greater variation.

Precipitation is measured by the Vaisala^{TM} transmitter with a proprietary piezoelectric sensor (Salmi and others, 2008). Basara and others (2009) concluded that piezoelectric sensors have the potential to underestimate rainfall when compared to tipping-bucket units, depending on rainfall intensity. Despite these differences, R^2 values greater than 0.95 between the Vaisala^{TM} transmitter and the tipping-bucket unit were calculated by Basara and others (2009), suggesting comparable results.

Air temperature, barometric pressure, and relative humidity are measured using a capacitive ceramic thermal sensor, a capacitive silicon pressure sensor, and a capacitive polymer moisture sensor, respectively, located inside a polycarbonate vented radiation shield. Based on manufacturer's stated range of measurements, accuracy, and resolution for these parameters (table 2), these methods meet the measurement criteria for the National Weather Service's Surface Observing Program (National Oceanic and Atmospheric Administration, 2010).

Table 2. Manufacturer's stated accuracy and resolution for the Vaisala™ WXT510/520 Weather Transmitter (adapted from Vaisala, 2008).

Range	Accuracy	Resolution
Air Temperature		
-52 to 60 degrees Celsius (°C)	±0.3°C at 20°C	0.1°C
Atmospheric Pressure		
600 to 1,100 Millibars (mbar)	±0.5 mbar at 0 to 30°C ±1 mbar at -52 to 60°C	0.1 mbar
Precipitation		
-	5%	0.01 millimeters with a 10-second duration
Relative Humidity		
0 to 100 % Relative Humidity (RH)	±3% RH at 0 to 90% RH ±5% RH at 90 to 100% RH	0.1% RH
Wind Speed		
0 to 60 meters per second (m/s)	the greater of ±0.3 m/s or ±3% for 0 to 35 m/s 5% for 36 to 60 m/s	0.1 m/s
Wind Direction		
0 to 360 degrees Azimuth (°)	±3.0° with a 0.25 second response time	1°

Wind direction, wind speed, air temperature, relative humidity, and barometric pressure are collected for each interval as instantaneous records every 4 minutes. Wind gusts represent the maximum wind speed for each 4-minute interval based on 4-second composite data. Rainfall values are collected as a total sum of all rain recorded during a 4-minute interval. All meteorological parameters are recorded in English units. To comply with scientific reporting standards, these data are converted to metric units using standard conversion factors. The method of data collection, the original English units for each parameter, the converted metric units, and a range of typical (expected) metric values are shown in table 3.

Table 3. Weather parameters, instrumentation, collection methods, and expected range of values.

[The expected ranges of values represent maximum and minimum 4-minute interval values, in the converted units, observed during the previous 4 years (2007–10) at the Grand Canyon Monitoring and Research Center and National Oceanic and Atmospheric Administration stations within the monitoring area. Values outside of this range do not necessarily indicate equipment error]

Parameter	Instrumentation	Method of collection	Data collection units	Converted units	Expected range of values*
Wind direction	Ultrasonic transducer	Instantaneous	degrees azimuth (true north)	not converted	0–360
Wind speed	Ultrasonic transducer	Instantaneous	miles per hour	meters per second	0–18
Wind gusts	Ultrasonic transducer	Maximum of 4-minute composite	miles per hour	meters per second	0–27
Air temperature	Ceramic thermal sensor	Instantaneous	degrees Fahrenheit	degrees Celsius	0–54
Relative humidity	Polymer moisture sensor	Instantaneous	relative percentage	not converted	0–100
Barometric pressure	Silicon pressure sensor	Instantaneous	inches mercury	millibars	845–1,015
Rainfall	Piezoelectric sensor	Total of 4-minute composite	inches	millimeters	0–25

*Values are in the converted units.

Quality Control

Data collected from the 14 automated weather stations were analyzed for potential inconsistencies and spurious data through outlier identification, graphical analysis, and comparative analysis. Outlier identification was conducted by flagging weather parameter values that were outside of the expected range during the initial review of the 4-minute interval records of the seven collected meteorological parameters (wind direction, wind speed, wind gust, temperature, barometric pressure, relative humidity, and rainfall). The expected range for each parameter is presented in table 3. The expected range for each parameter was determined based on the range of values within the 2007 through 2010 datasets (Draut and others, 2009a, 2009b, 2010b; Dealy and others, 2014) and on historical maximum and minimum values published by the NOAA National Climatic Data Center (NCDC) for Page, Arizona (station GHCND:USW00053164), Paria Point, Arizona (station GHCND:USR0000APAR), and Phantom Ranch, Arizona (station GHCND:USC00026471).

To identify potentially spurious data within the expected range of parameter values, deviations from natural trends were identified by graphical analysis. Graphical analysis was conducted by plotting values within Microsoft® Excel and Matlab™ R2013b. Records with values that deviated from diurnal, nocturnal, or seasonal trends were inspected to examine whether they represented real phenomena or were likely spurious data. Comparative analysis was conducted on parameters, such as rainfall, that do not necessarily follow daily or monthly trends. This analysis involved comparisons of graphical and tabular data for each weather station and the nearest upstream and downstream sites. Records with potentially spurious data were further inspected. Determination, justification, and rectification of anomalies have been included in appendix 2.

Results

Meteorological data collected by GCMRC at each of the 14 automated weather stations within the Colorado River Corridor for the reporting period are provided in appendix 3. Appendix 3 contains 4-minute interval data for each of the automated weather stations, tab separated by parameter (wind direction, wind speed, wind gusts, air temperature, relative humidity, barometric pressure, and rainfall. In addition to the data collected during the reporting period, appendix 4 provides, for the first time in digital format, previously reported 4-minute interval data collected by the automated weather stations from February 2007 through December 2010.

A summary of meteorological data presented in appendix 3 is provided graphically in time-series plots in figures 3–9. Figure 3 presents mean wind speed and maximum wind gusts by wind direction. Mean and maximum wind speeds are affected by the frequency of wind direction change. For comparison, the number (frequency) of 4-minute records used to calculate these statistics was included, by azimuth, in the time-series plot as well as wind vector sums. Wind vector sums were calculated for winds greater than 2 m/s, a minimum threshold for sand transport (Draut and others, 2009a, 2009b, 2010b; Dealy and others, 2014). Time-series plots in figure 3 are presented by season based on typical solstice/equinox dates and the available data recorded. For 2011, winter was defined as from January 1 (first record) to March 20, spring was from March 20 to June 21, summer was from June 21 to September 22, and fall was from September 22 to November 22 (last record). For 2013, spring was defined as from April 27 (first record) to June 21, summer was from June 21 to September 22, fall was from September 22 to December 21, and winter was from December 21 to December 31 (last record).

As gaps within the seasonal data were present, the percentage of data used for the wind speed-direction polar plots has been included in the figure description. Figures 4–8 present maximum wind gusts and mean wind speed, air temperature, relative humidity, and barometric pressure summarized by daily and nightly values. Daily 12-hour summary values were derived from parameters collected between 6 a.m. (0600) and 6 p.m. (1800), and nightly 12-hour summary values were derived from parameters collected between 6 p.m. (1800) and 6 a.m. (0600). Figure 9 presents cumulative daily rain totals with the maximum daily 10-minute rainfall intensity, a metric for precipitation-induced erosion (Collins and others, in press). Values for 10-minute intensity (in millimeters per hour) were calculated from the 4-minute interval rainfall data using the following equation adapted from Ward and Elliot (1995):

$$I = \left(r_1 + r_2 + \frac{r_3}{2}\right) * 6$$

Where r_1, r_2, and r_3 are consecutive 4-minute intervals of total rainfall, in millimeters.
A summary of the daily rainfall totals for the reporting period is provided in table 4.

Table 4. Rainfall totals for the reporting period in millimeters per day.
[Table 4 is a Microsoft® Excel file available for download at *http://pubs.usgs.gov/of/2014/1247*]

Discussion and Meteorological Context

Weather conditions during the reporting period are expected to be atypical because regional weather patterns in the Southwestern United States were warmer and drier than average (National Oceanic and Atmospheric Administration National Climatic Data Center, 2011, 2012, 2013). In 2011, much of the Southern United States experienced some degree of drought. Below-average rainfall and above-average air temperatures during the monsoon season (July–October) contributed to local areas of severe to extreme drought in northern Arizona (National Oceanic and Atmospheric Administration National Climatic Data Center, 2011). These conditions persisted through much of 2012, with the Lower Colorado River Basin experiencing the 24th driest year on record (National Oceanic and Atmospheric Administration National Climatic Data Center, 2012). Monsoon season temperatures continued to be high through 2013, and precipitation totals during this season exceeded normal conditions (116-year average) (National Oceanic and Atmospheric Administration National Climatic Data Center, 2013). Above-average precipitation during the summer and fall of 2013 was sufficient to alleviate some, but not all, of the drought conditions within the Lower Colorado River Basin (National Oceanic and Atmospheric Administration National Climatic Data Center, 2013, 2014). Based on the Palmer Hydrologic Drought Index, short-term analysis suggests drought conditions will persist into 2014 (National Oceanic and Atmospheric Administration National Climatic Data Center, 2014).

Oceanic temperature cycles in the Pacific known as El Niño/Southern Oscillation (ENSO) can have a role in weather conditions within the Southwestern United States (Kumar and Hoerling, 1998), particularly in strong El Nino (warm) years, where cool season precipitation is typically above average, and in strong La Niña (cool) years, where annual precipitation is typically below average (McPhaden and Others, 2006; Wolter and Timlin, 2011). During the reporting period, ENSO was likely a minor factor in regional weather because the Pacific Ocean was in a weak to neutral ENSO state (National Oceanic and Atmospheric Administration National Climatic Data Center, 2011, 2012). In 2011, a weak La Niña (cool) state was present for most of the year (National Oceanic and Atmospheric Administration National Climatic Data Center, 2011). By April 2012, the ENSO had transitioned to a neutral state, where it remained through 2013 (National Oceanic and Atmospheric Administration National Climatic Data Center, 2012, 2013).

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Figure 3. Polar plots showing seasonal wind speed means, maximum wind gusts, wind vector sums for wind speeds greater than 2 meters per second, and the total number (frequency) of 4-minute records by azimuth (in respect to true north). Seasonal statistics were calculated for 2011 based on the following dates—winter from January 1 (first record) to March 20 (28,440 possible records), spring from March 20 to June 21 (33,480 possible records), summer from June 21 to September 22 *(*33,480 possible records*),* and fall from September 22 to November 22 (last record) (21,746 possible records). Seasonal statistics were calculated for 2013 based on the following dates— spring was from April 27 (first record) to June 21 (33,480 possible records), summer from June 21 to September 22 (33,480 possible records), fall from September 22 to December 21 (32,400 possible records), and winter from December 21–December 31 (last record) (3,600 possible records). Data were not collected between November 22, 2011, and April 27, 2013. All polar plots represent the maximum number of possible 4-minute records unless otherwise stated.

Station AZ C:02:0071

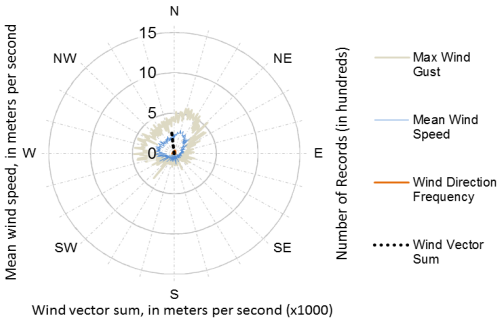
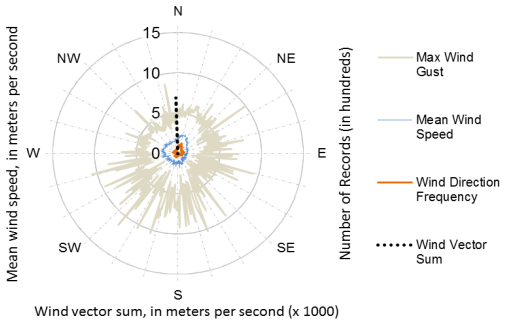
	2011	2013
Winter Jan 1-Mar 20 (2011), Dec 21-Dec 31 (2013)	No Data Recorded in 2011	
Spring Mar 20-Jun 21	No Data Recorded in 2011	No Data Recorded in 2013
Summer Jun21-Sep 22	No Data Recorded in 2011	No Data Recorded in 2013
Fall Sep 22-Dec 21	No Data Recorded in 2011	

Figure 3. (a) Station AZ C:02:0071 seasonal wind speed-direction plots. In 2013, 52 percent of the possible records were collected during fall

Station AZ C:02:0070

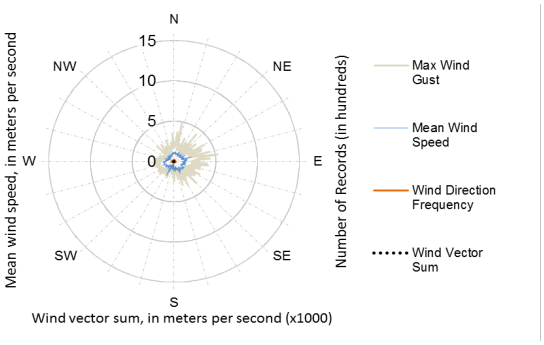
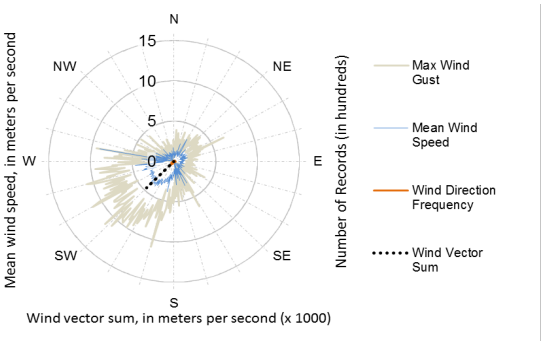
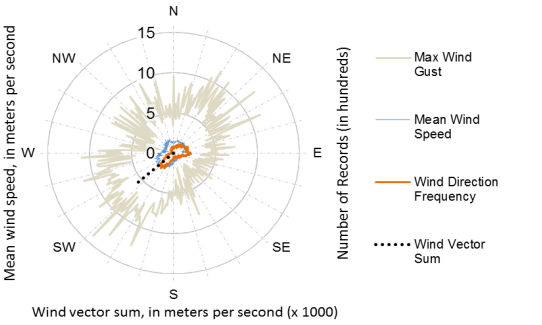
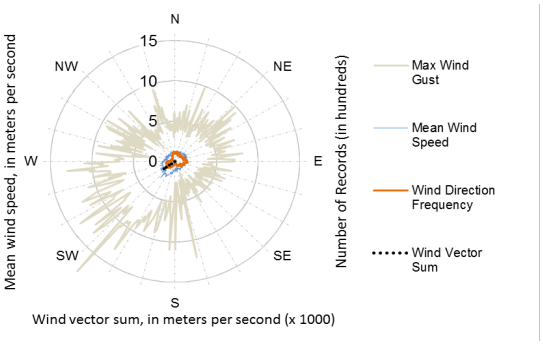
	2011	2013
Winter Jan 1-Mar 20 (2011), Dec 21-Dec 31 (2013)	No Data Recorded in 2011	
Spring Mar 20-Jun 21	No Data Recorded in 2011	
Summer Jun21-Sep 22	No Data Recorded in 2011	
Fall Sep 22-Dec 21	No Data Recorded in 2011	

Figure 3. (b) Station AZ C:02:0070 seasonal wind speed-direction plots. In 2013, 17 percent of the possible records were collected during spring and 89 percent were collected during winter.

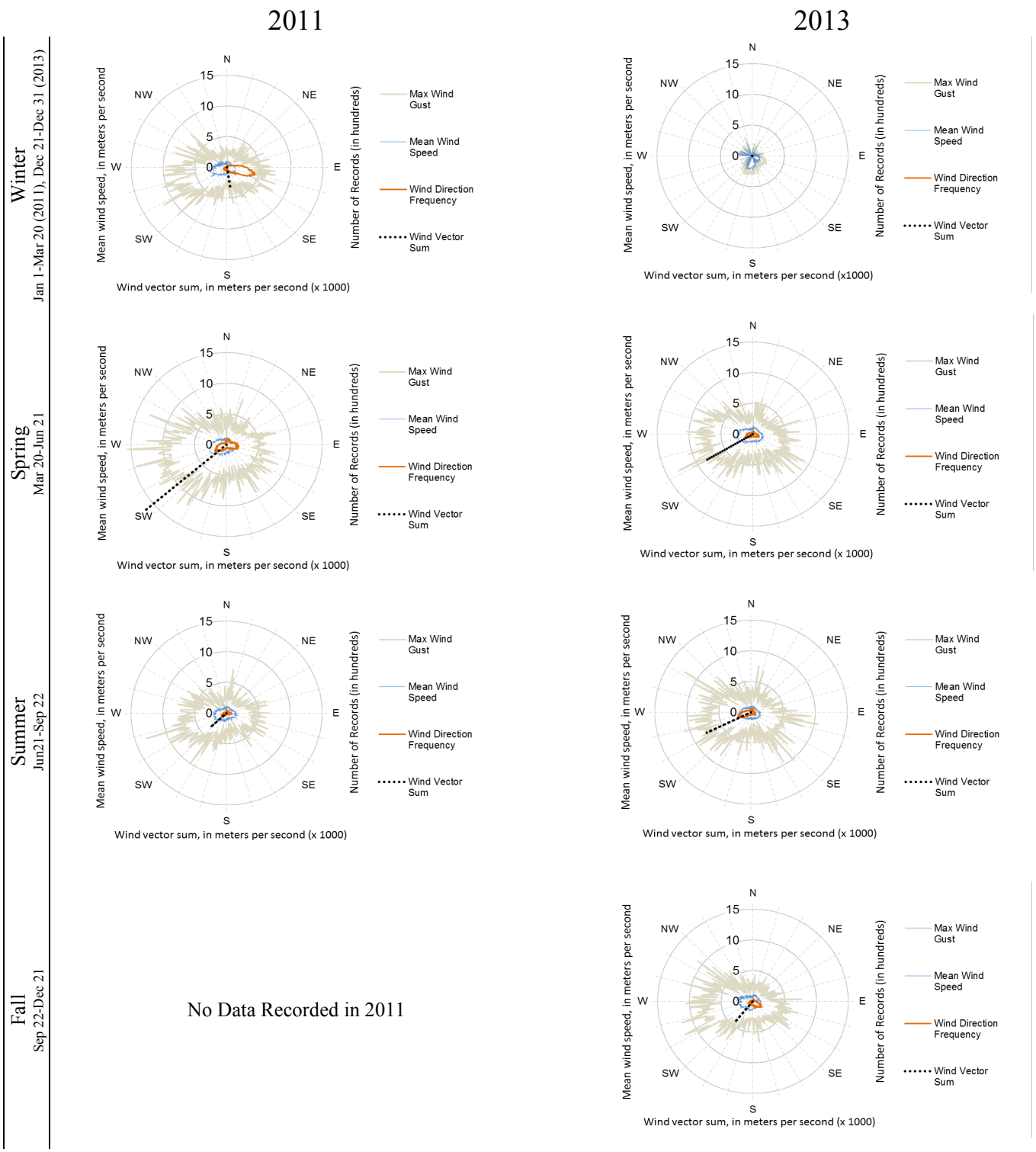


Figure 3. (c) Station AZ C:05:0031 Upper seasonal wind speed-direction plots. In 2011, 40 percent of the possible records were collected during summer. In 2013, 20 percent of the possible records were collected during winter, 92 percent were collected during spring, 68 percent were collected during summer, and 57 percent were collected during fall.

Station AZ C:05:0031 Lower

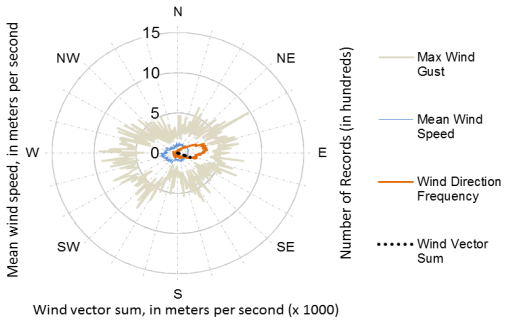
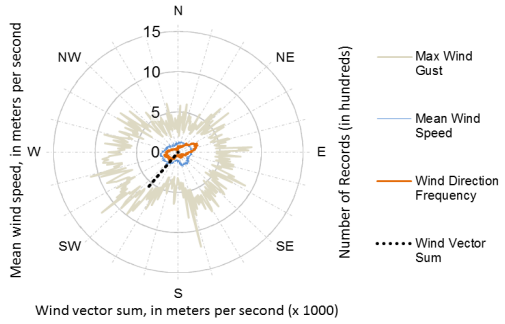
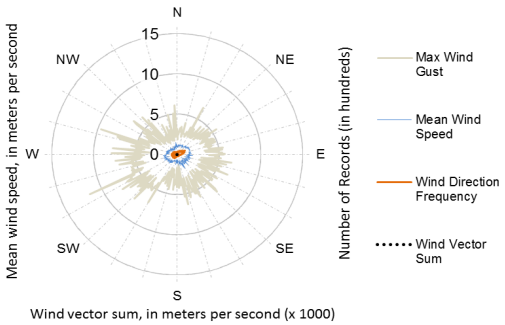
	2011	2013
Winter Jan 1-Mar 20 (2011), Dec 21-Dec 31 (2013)		No Data Recorded in 2013
Spring Mar 20-Jun 21		No Data Recorded in 2013
Summer Jun21-Sep 22		No Data Recorded in 2013
Fall Sep 22-Dec 21	No Data Recorded in 2011	No Data Recorded in 2013

Figure 3. (d) Station AZ C:05:0031 Lower seasonal wind speed-direction plots. In 2011, 40 percent of the possible records were collected during summer.

Station AZ C:13:0365 Upper

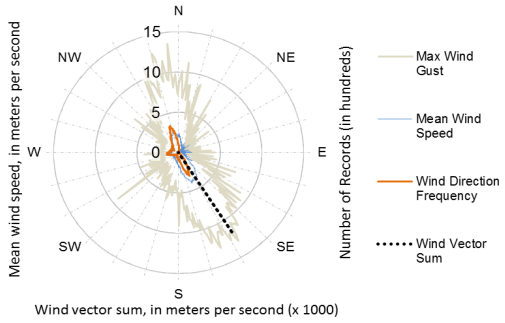
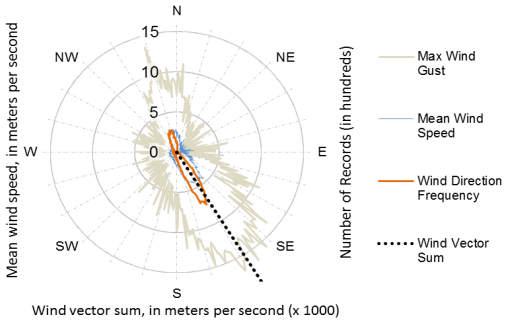
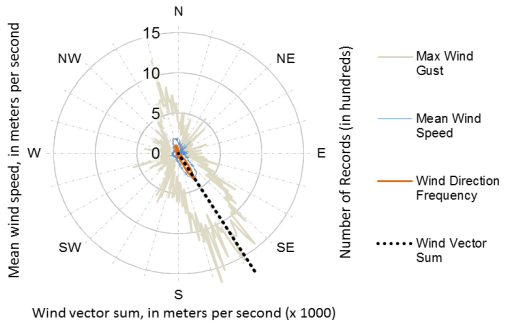
	2011	2013
Winter Jan 1-Mar 20 (2011), Dec 21-Dec 31 (2013)		No Data Recorded in 2013
Spring Mar 20-Jun 21		No Data Recorded in 2013
Summer Jun21-Sep 22		No Data Recorded in 2013
Fall Sep 22-Dec 21	No Data Recorded in 2011	No Data Recorded in 2013

Figure 3. (e) Station AZ C:13:0365 Upper seasonal wind speed-direction plots. In 2011, 42 percent of the possible records were collected during summer.

Station AZ C:13:0365 Lower

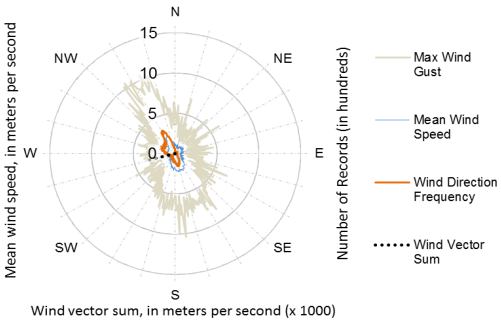
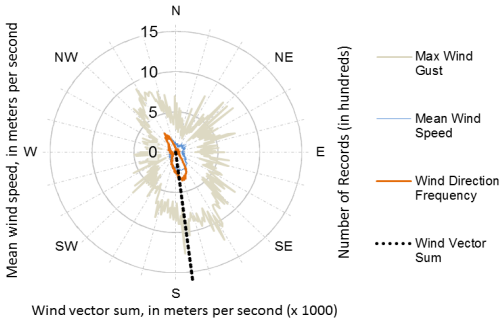
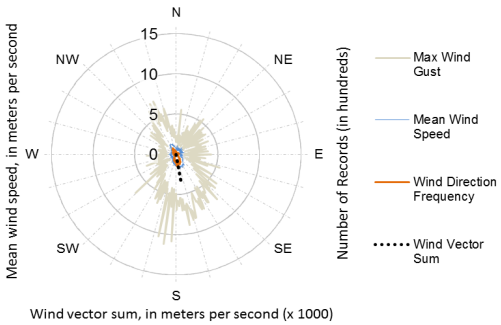
	2011	2013
Winter Jan 1-Mar 20 (2011), Dec 21-Dec 31 (2013)		No Data Recorded in 2013
Spring Mar 20-Jun 21		No Data Recorded in 2013
Summer Jun21-Sep 22		No Data Recorded in 2013
Fall Sep 22-Dec 21	No Data Recorded in 2011	No Data Recorded in 2013

Figure 3. (f) Station AZ C:13:0365 Lower seasonal wind speed-direction plots. In 2011, 42 percent of the possible records were collected during summer.

Station AZ C:13:0006

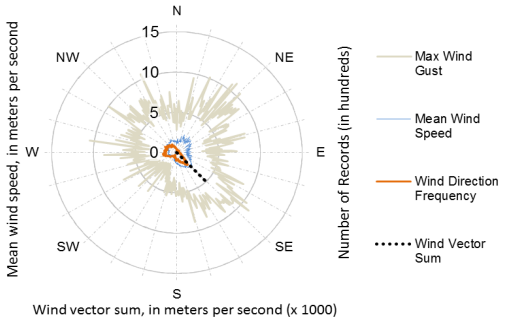
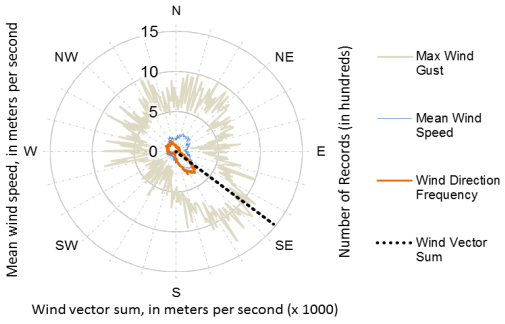
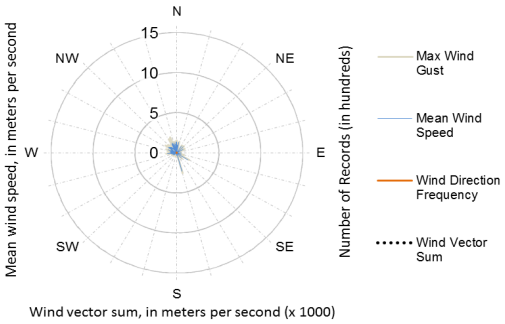
	2011	2013
Winter Jan 1-Mar 20 (2011), Dec 21-Dec 31 (2013)		No Data Recorded in 2013
Spring Mar 20-Jun 21		No Data Recorded in 2013
Summer Jun21-Sep 22		No Data Recorded in 2013
Fall Sep 22-Dec 21	No Data Recorded in 2011	No Data Recorded in 2013

Figure 3. (g) Station AZ C:13:0006 seasonal wind speed-direction plots. In 2011, 4 percent of the possible records were collected during summer.

Station AZ C:13:0336

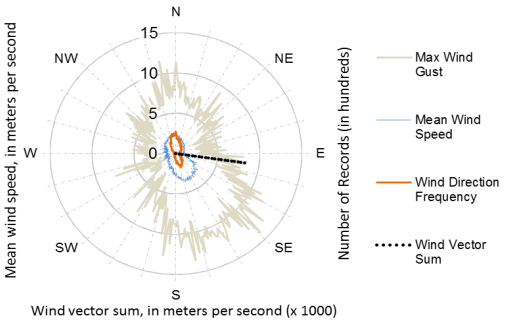
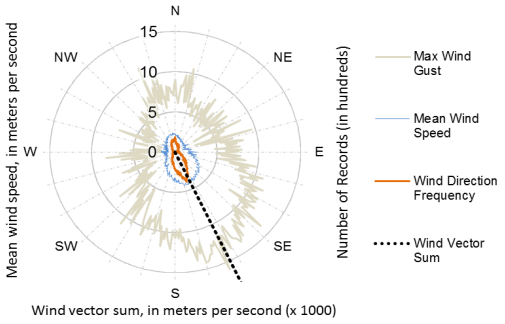
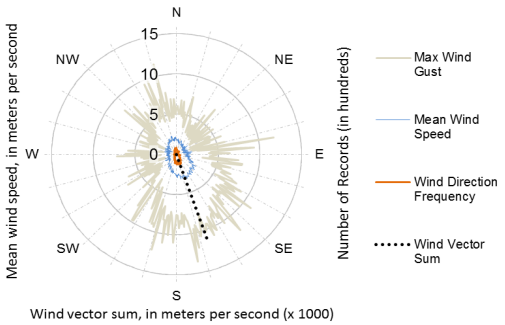
	2011	2013
Winter Jan 1-Mar 20 (2011), Dec 21-Dec 31 (2013)		No Data Recorded in 2013
Spring Mar 20-Jun 21		No Data Recorded in 2013
Summer Jun21-Sep 22		No Data Recorded in 2013
Fall Sep 22-Dec 21	No Data Recorded in 2011	No Data Recorded in 2013

Figure 3. (h) Station AZ C:13:0336 seasonal wind speed-direction plots. In 2011, 45 percent of the possible records were collected during summer.

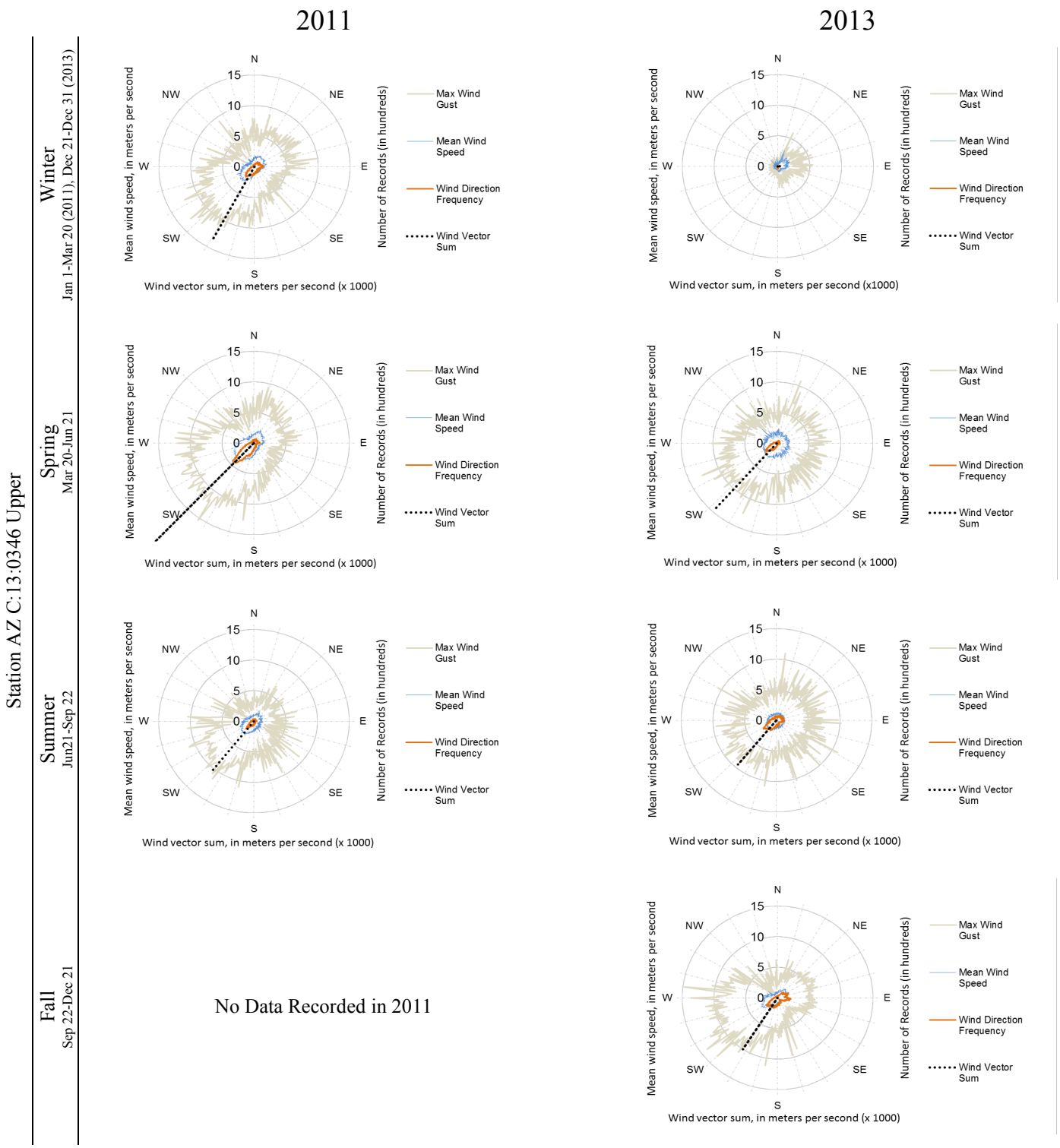


Figure 3. (i) Station AZ C:13:0346 Upper seasonal wind speed-direction plots. In 2011, 45 percent of the possible records were collected during summer. In 2013, 92 percent of the possible records were collected during spring.

Station AZ C:13:0346 Lower

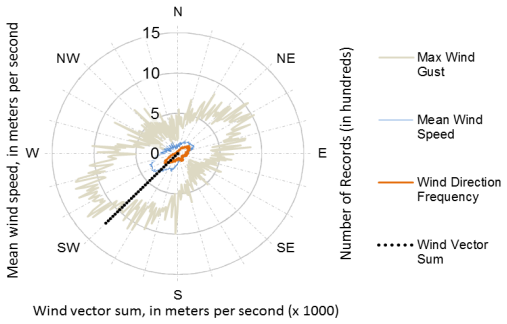
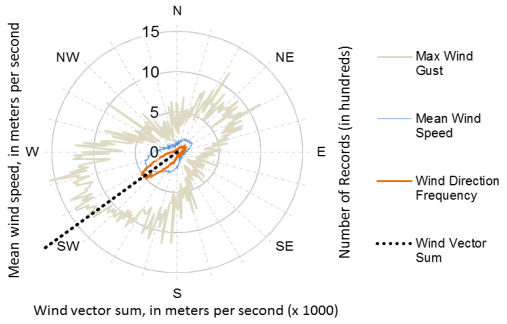
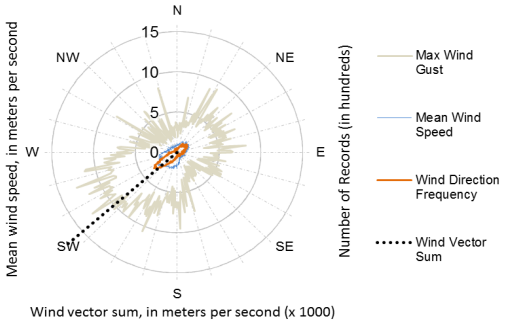
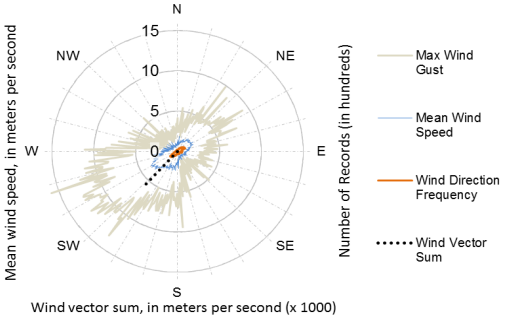
	2011	2013
Winter Jan 1-Mar 20 (2011), Dec 21-Dec 31 (2013)		No Data Recorded in 2013
Spring Mar 20-Jun 21		No Data Recorded in 2013
Summer Jun21-Sep 22		No Data Recorded in 2013
Fall Sep 22-Dec 21		No Data Recorded in 2013

Figure 3. (j) Station AZ C:13:0346 Lower seasonal wind speed-direction plots. In 2011, 94 percent of the possible records were collected during winter, 99 percent were collected during spring, 89 percent were collected during summer, and 61 percent were collected during fall.

Station AZ B:10:0225

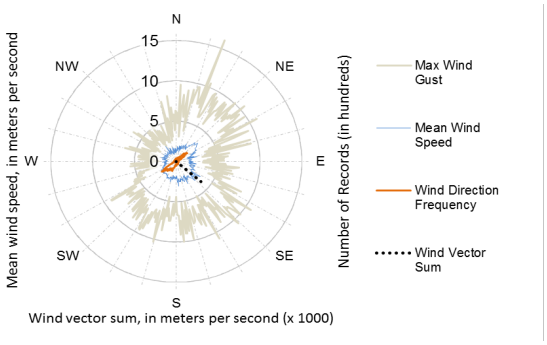
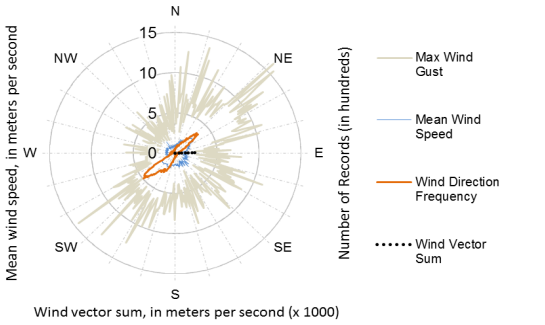
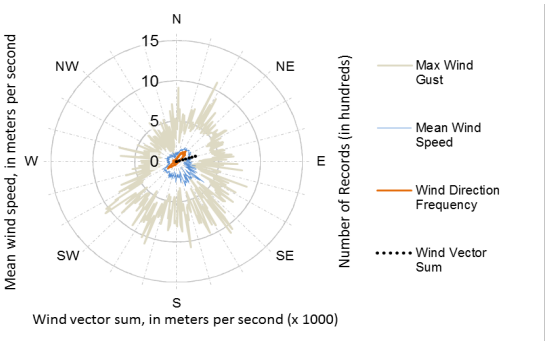
	2011	2013
Winter Jan 1-Mar 20 (2011), Dec 21-Dec 31 (2013)	No Data Recorded in 2011	No Data Recorded in 2013
Spring Mar 20-Jun 21	No Data Recorded in 2011	
Summer Jun21-Sep 22	No Data Recorded in 2011	
Fall Sep 22-Dec 21	No Data Recorded in 2011	

Figure 3. (k) Station AZ B:10:0225 seasonal wind speed-direction plots. In 2013, 83 percent of the possible records were collected during spring and 44 percent were collected during fall.

Station AZ B:11:0281

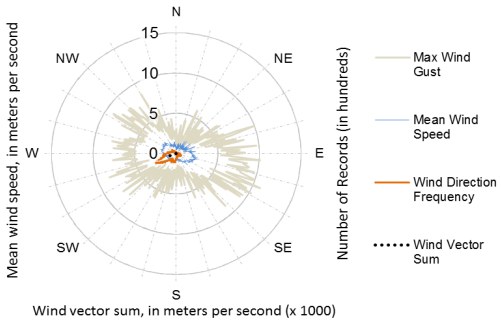
	2011	2013
Winter Jan 1-Mar 20 (2011), Dec 21-Dec 31 (2013)		No Data Recorded in 2013
Spring Mar 20-Jun 21	No Data Recorded in 2011	No Data Recorded in 2013
Summer Jun21-Sep 22	No Data Recorded in 2011	No Data Recorded in 2013
Fall Sep 22-Dec 21	No Data Recorded in 2011	No Data Recorded in 2013

Figure 3. (l) Station AZ B:11:0281 seasonal wind speed-direction plots. In 2011, 73 percent of the possible records were collected during winter.

Station AZ A:15:0033

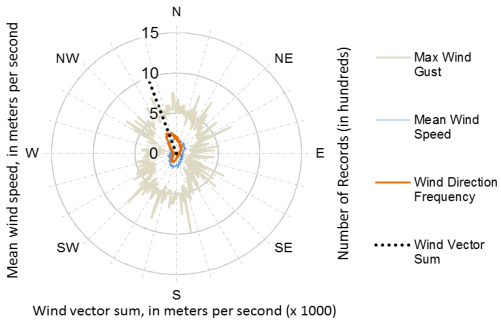
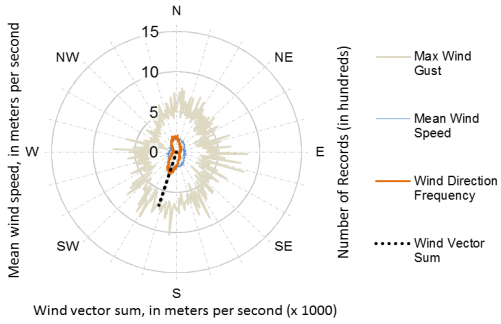
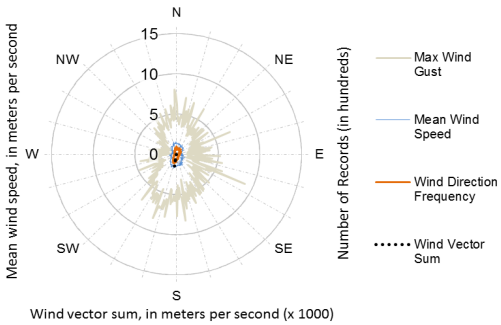
	2011	2013
Winter Jan 1-Mar 20 (2011), Dec 21-Dec 31 (2013)		No Data Recorded in 2013
Spring Mar 20-Jun 21		No Data Recorded in 2013
Summer Jun21-Sep 22		No Data Recorded in 2013
Fall Sep 22-Dec 21	No Data Recorded in 2011	No Data Recorded in 2013

Figure 3. (m) Station AZ A:15:0033 seasonal wind speed-direction plots. In 2011, 49 percent of the possible records were collected during summer.

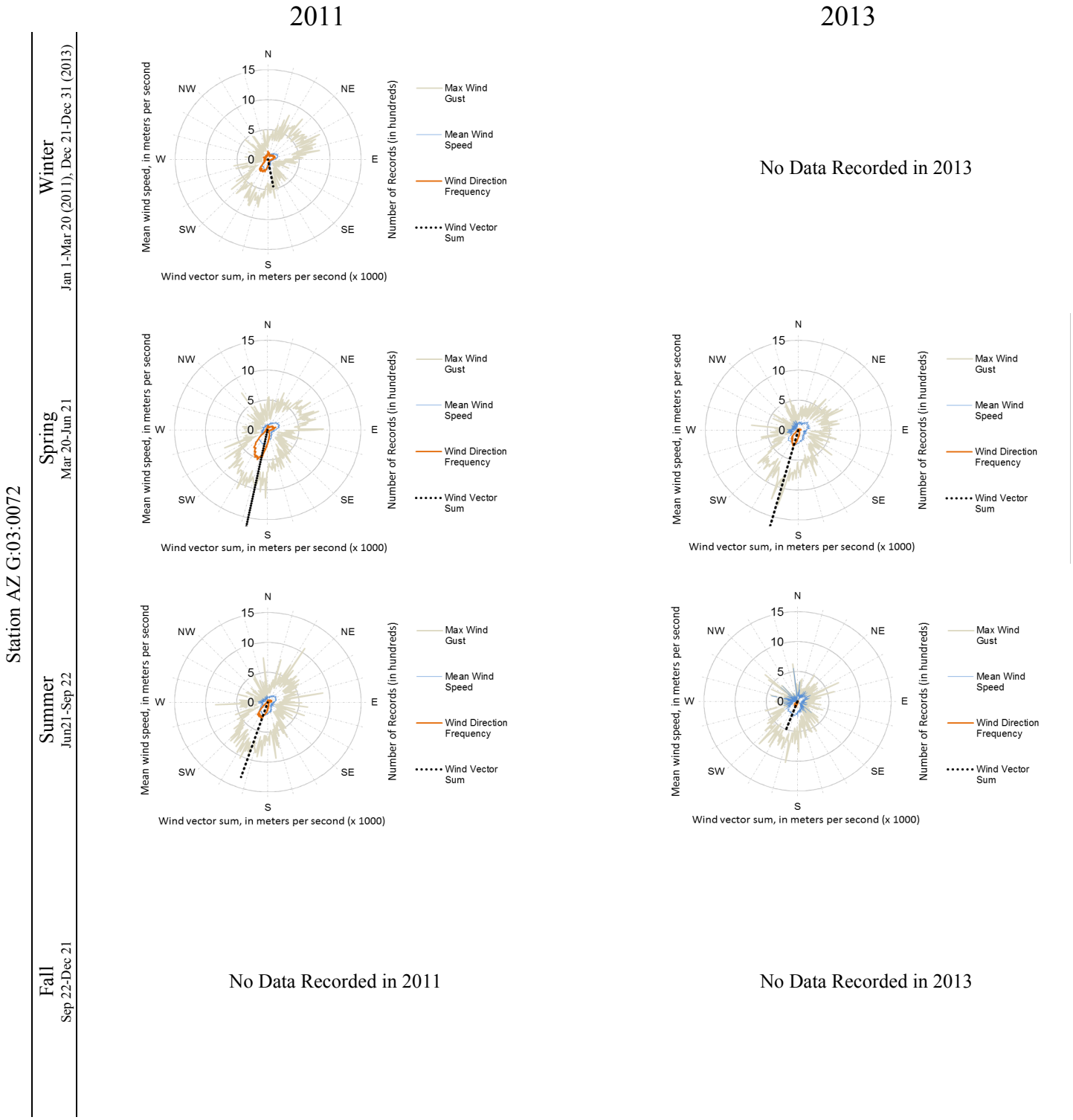


Figure 3. (n) Station AZ G:03:0072 seasonal wind speed-direction plots. In 2011, 54 percent of the possible records were collected during summer. In 2013, 75 percent of the possible records were collected during spring and 15 percent were collected during summer.

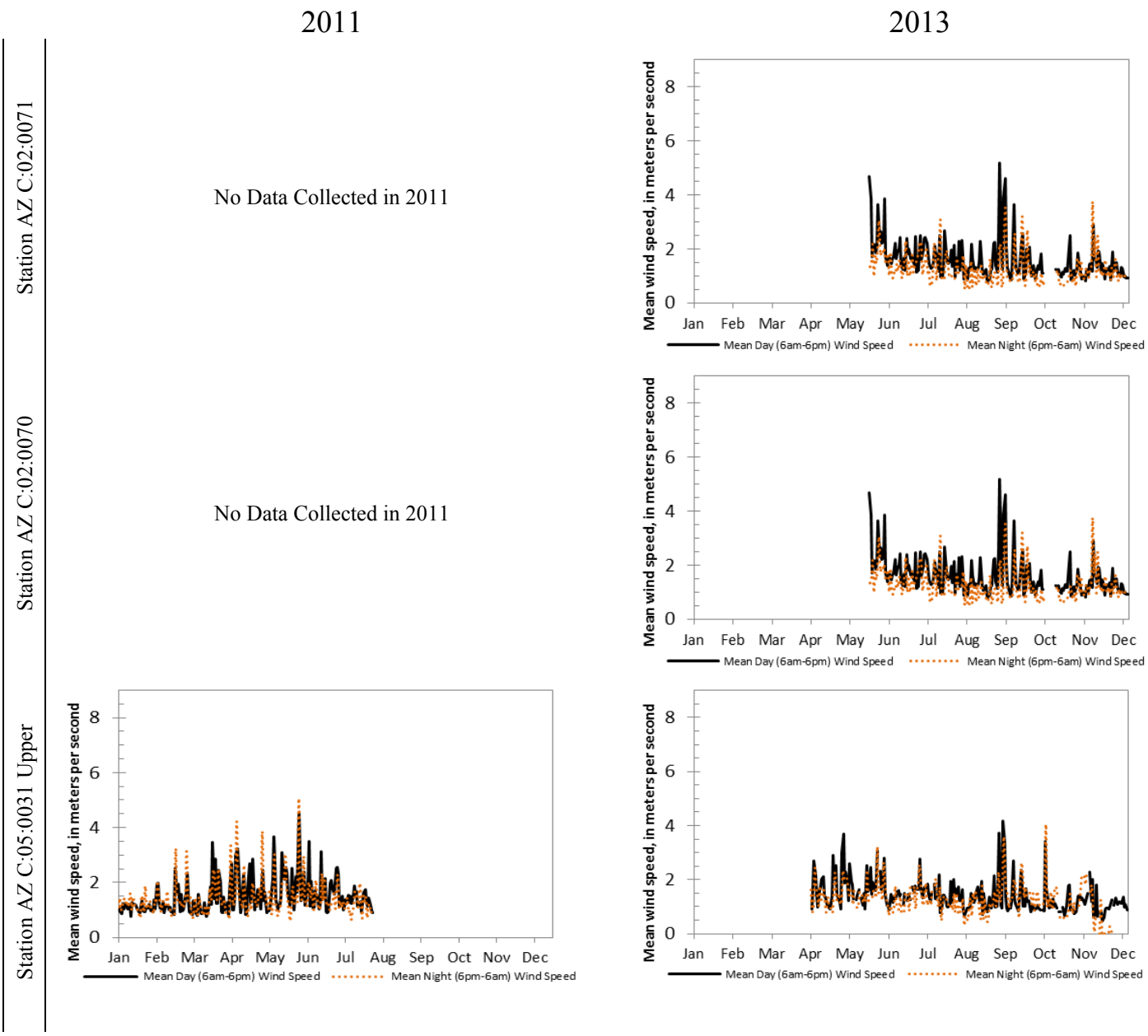


Figure 4. Graphs showing mean wind speeds recorded for 12-hour day (6 a.m.–6 p.m.) and night (6 p.m.–6 a.m.), January 1, 2011, through December 31, 2013. Data were not collected between November 22, 2011, and April 27, 2013.

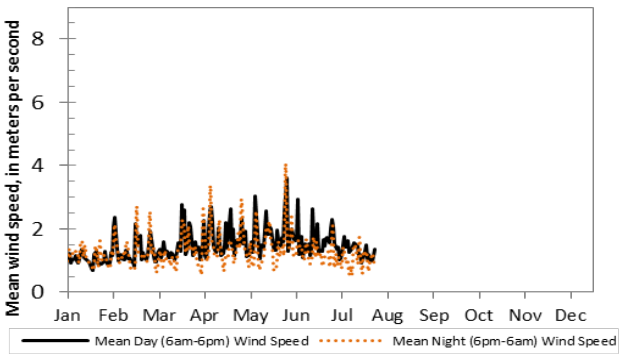
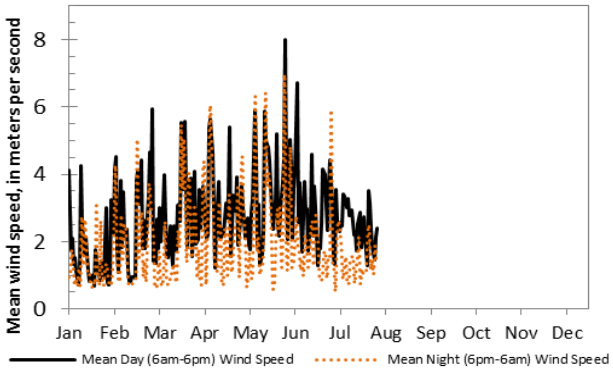
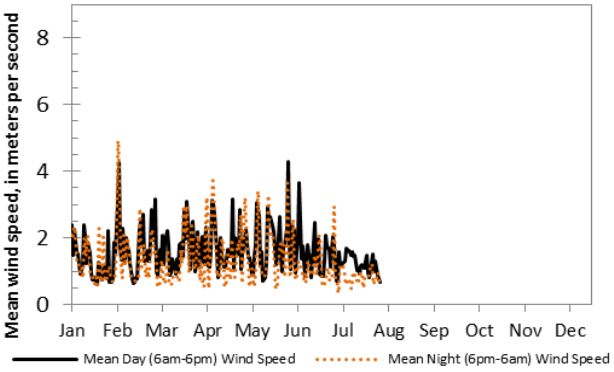
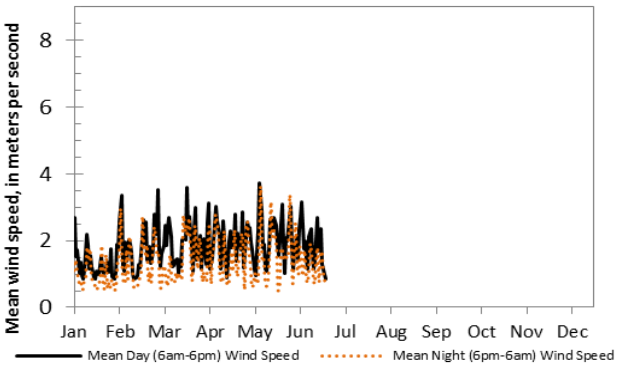
	2011	2013
Station AZ C:05:0031 Lower		No Data Collected in 2013
Station AZ C:13:0365 Upper		No Data Collected in 2013
Station AZ C:013:0365 Lower		No Data Collected in 2013
Station AZ C:013:0006		No Data Collected in 2013

Figure 4.—Continued

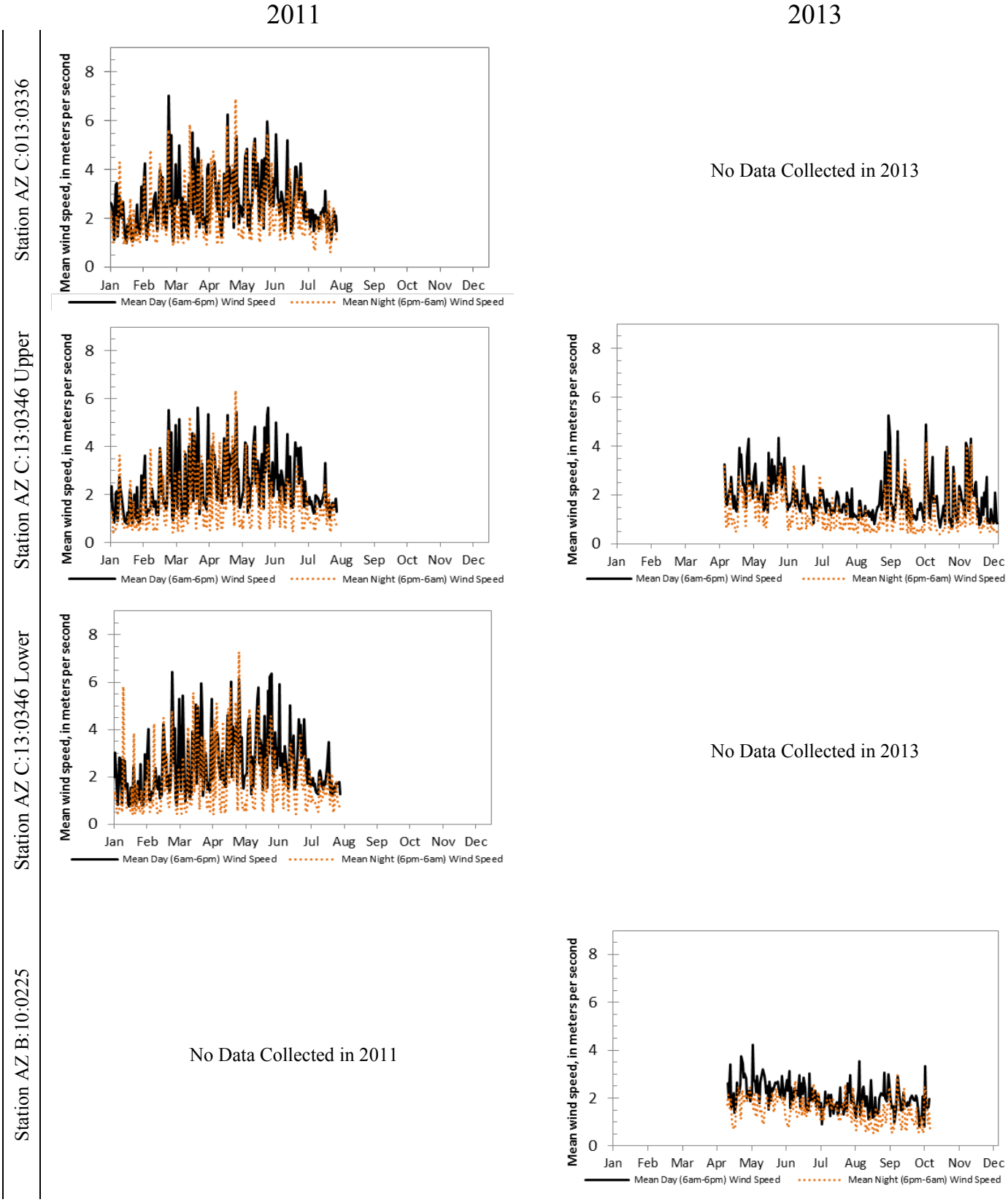


Figure 4.—Continued

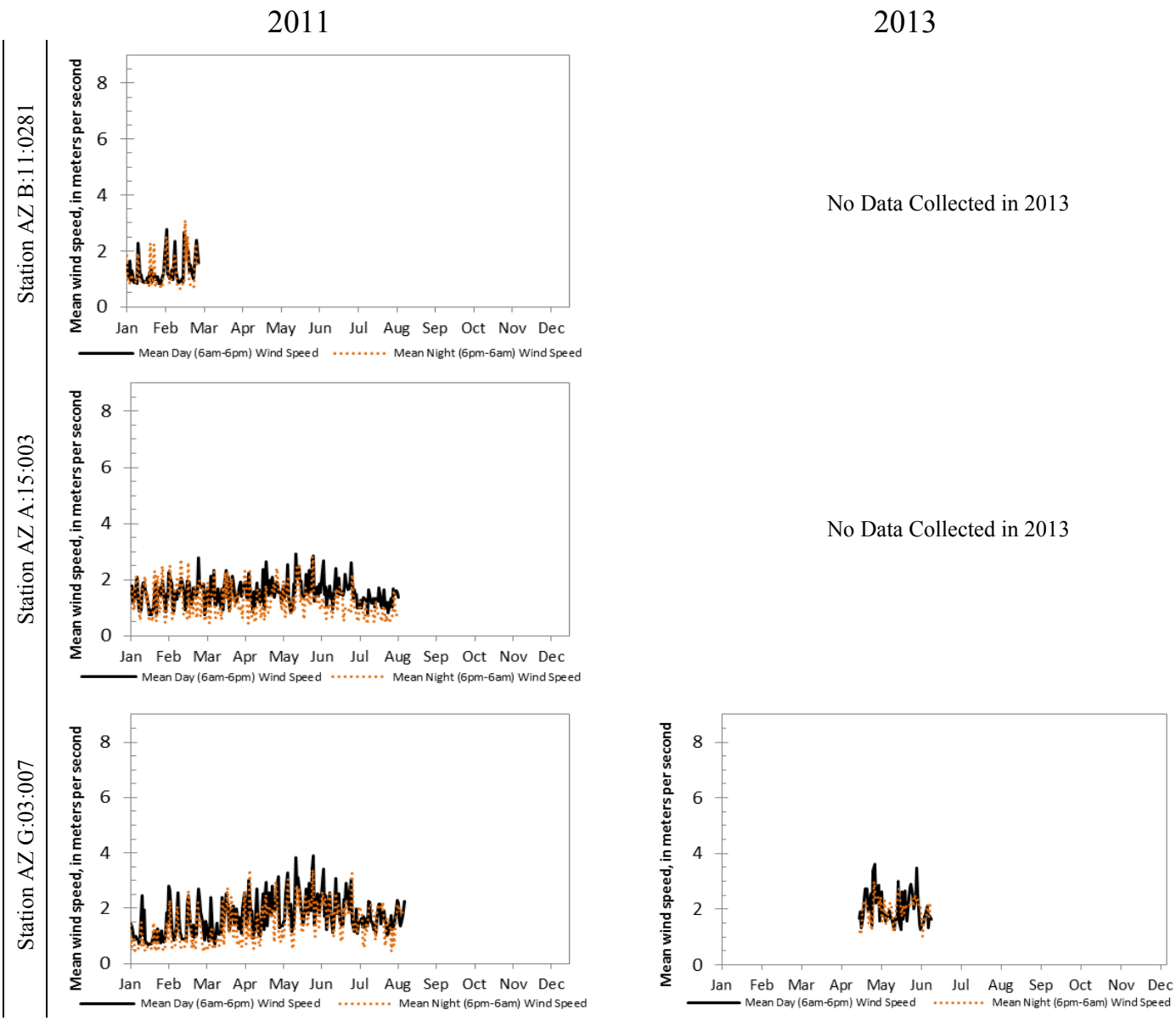


Figure 4.—Continued

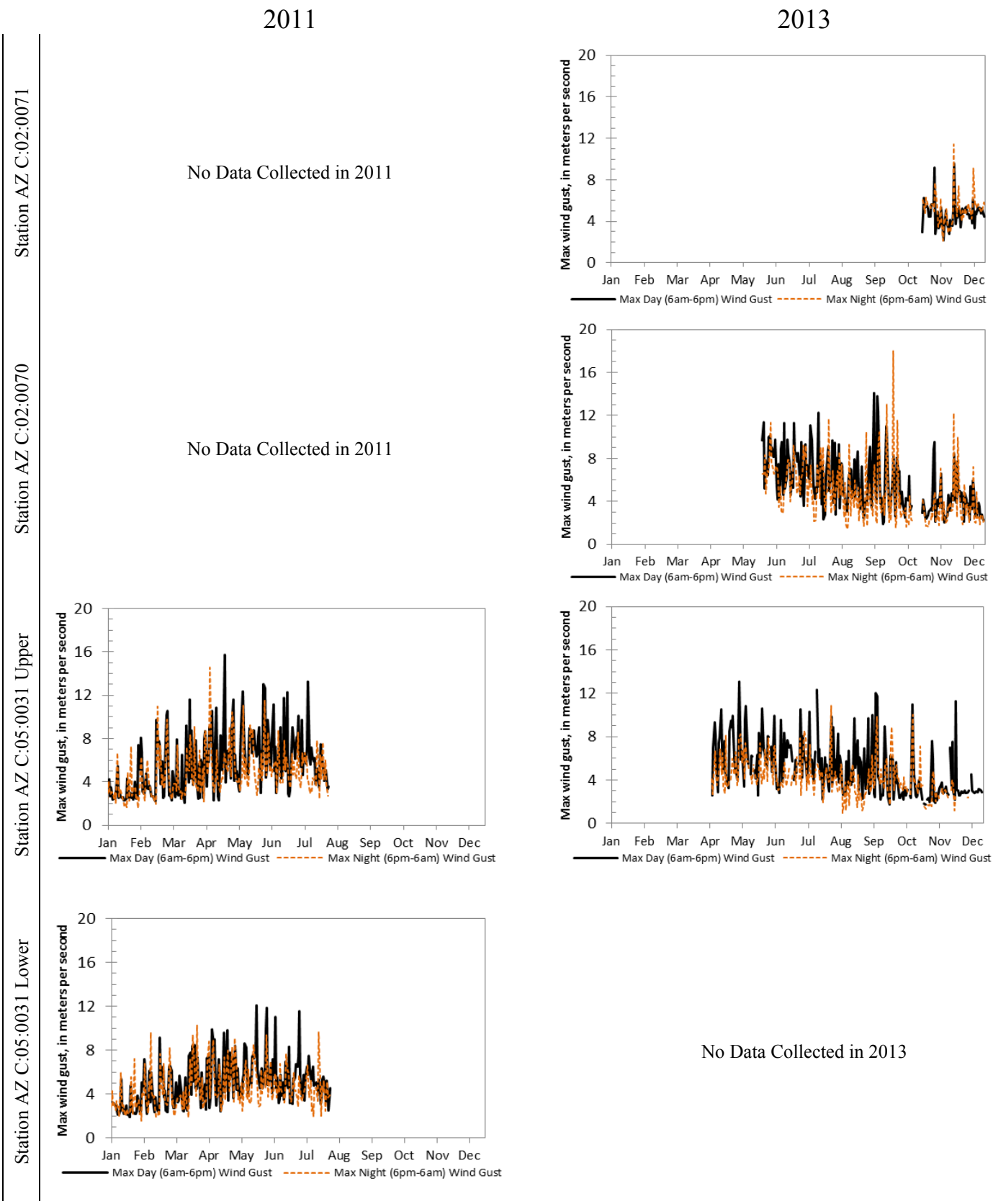


Figure 5. Graphs showing maximum wind gusts recorded for 12-hour day (6 a.m.–6 p.m.) and night (6 p.m.–6 a.m.), January 1, 2011, through December 31, 2013. Data were not collected between November 22, 2011, and April 27, 2013.

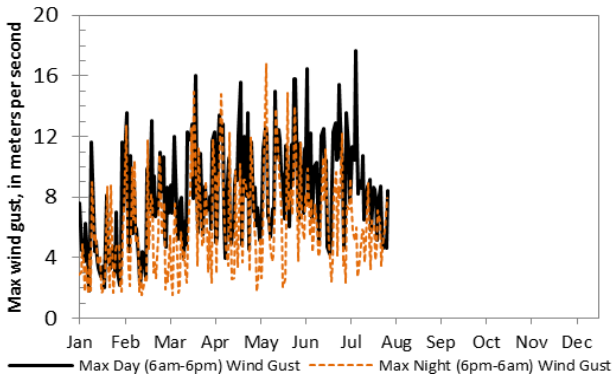
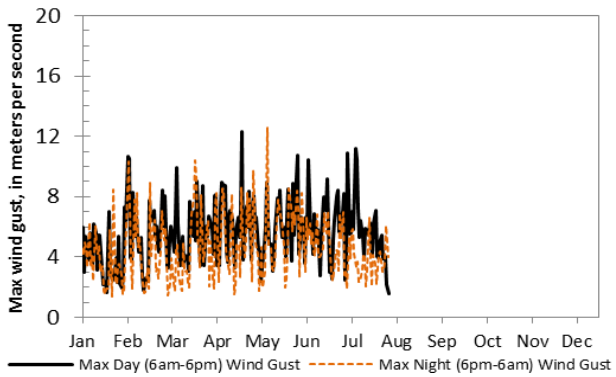
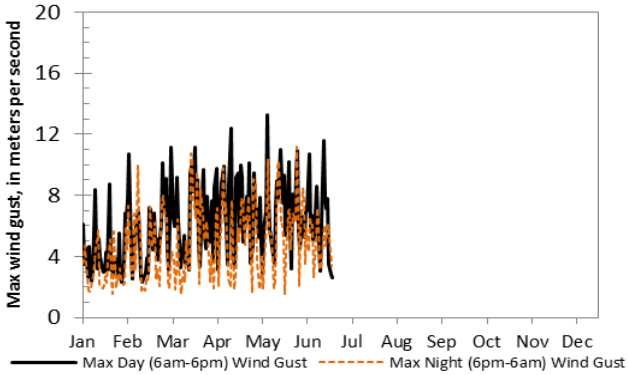
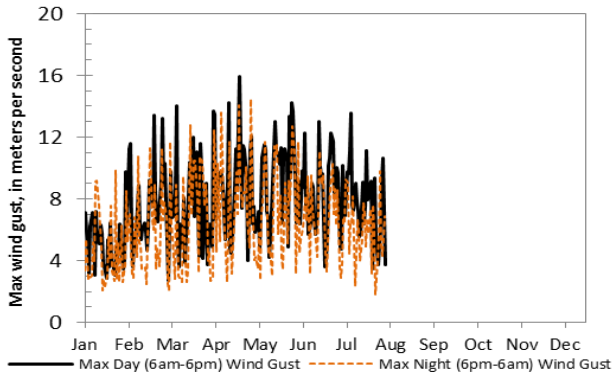
	2011	2013
Station AZ C:13:0365 Upper		No Data Collected in 2013
Station AZ C:013:0365 Lower		No Data Collected in 2013
Station AZ C:013:0006		No Data Collected in 2013
Station AZ C:013:0336		No Data Collected in 2013

Figure 5.—Continued

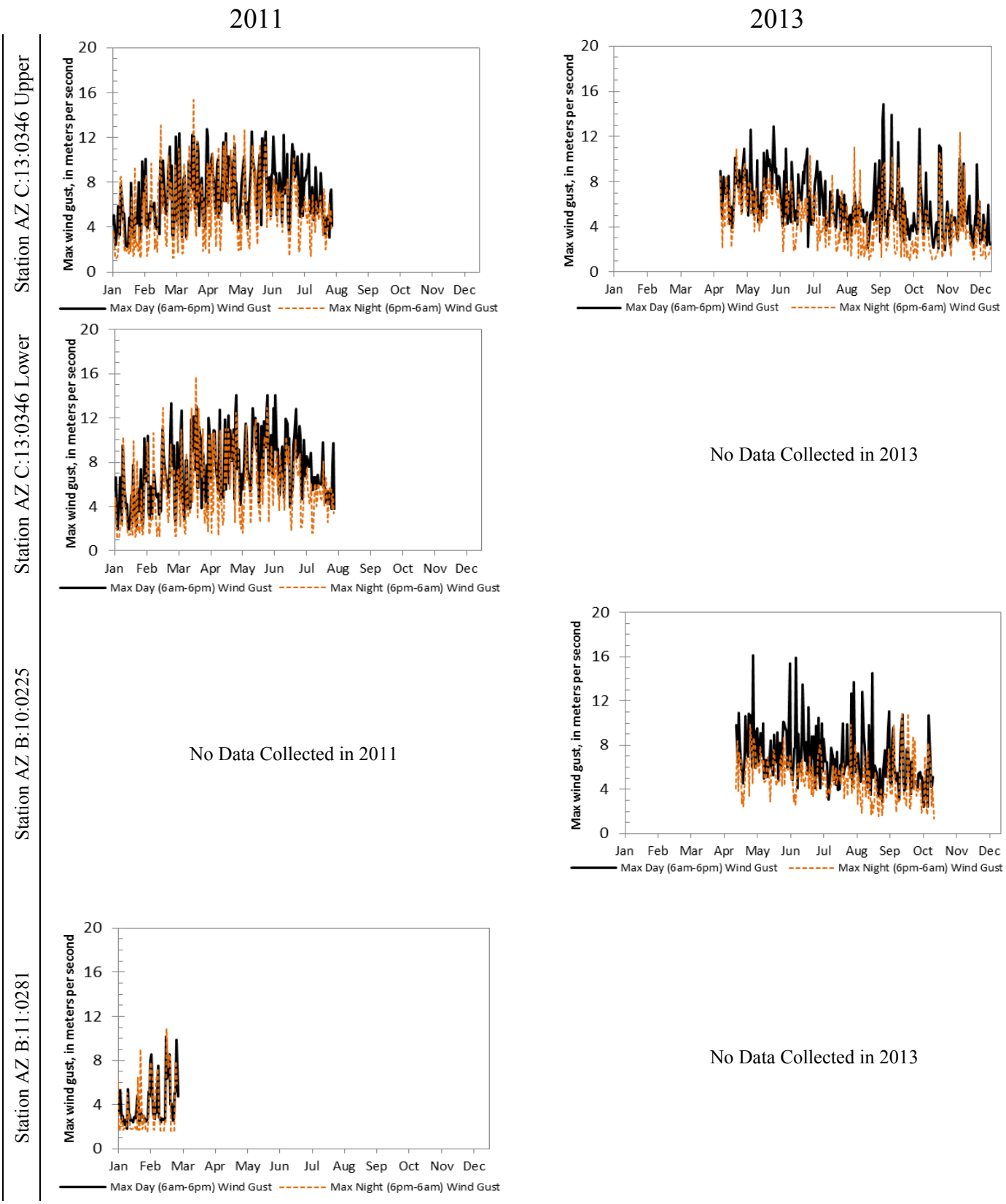


Figure 5.—Continued

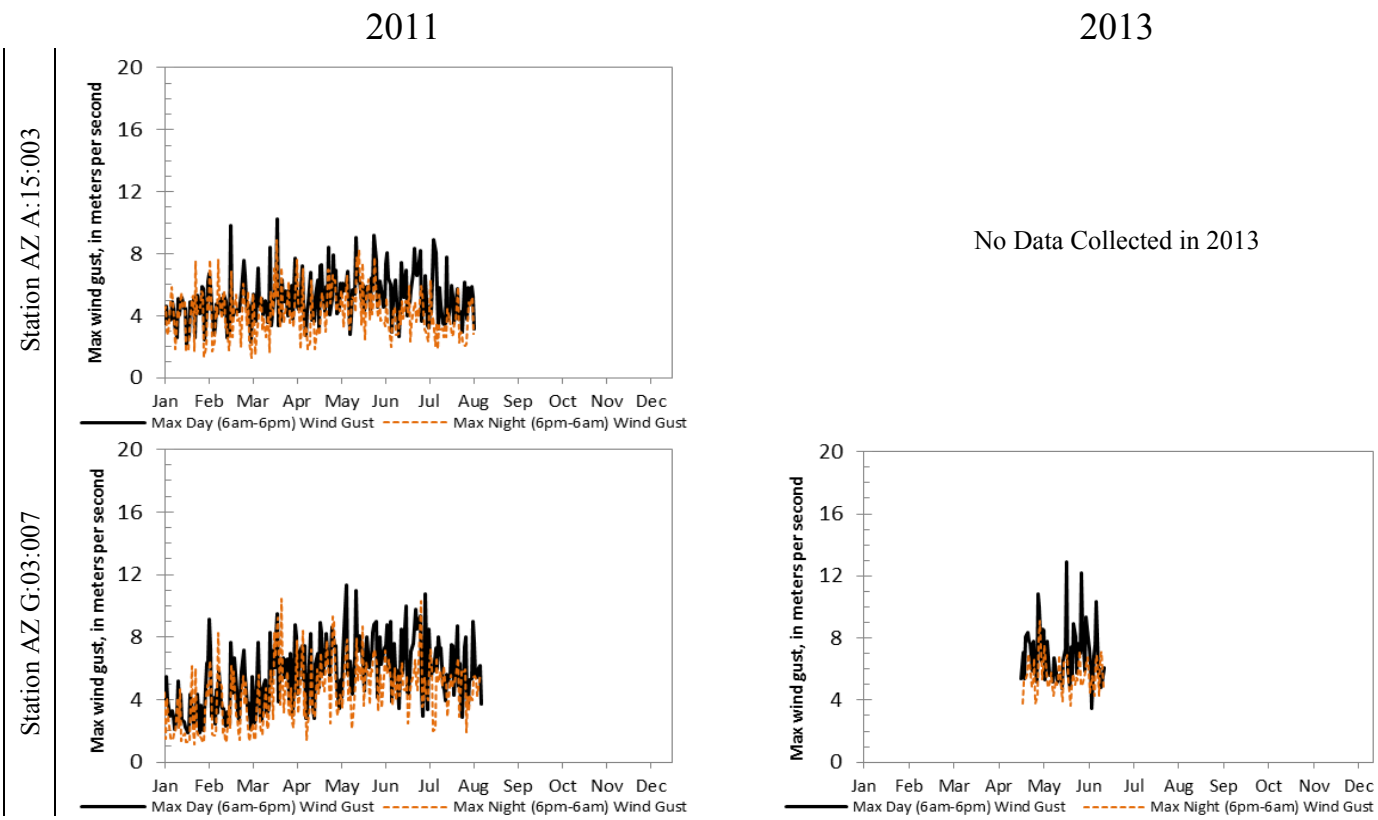


Figure 5.—Continued

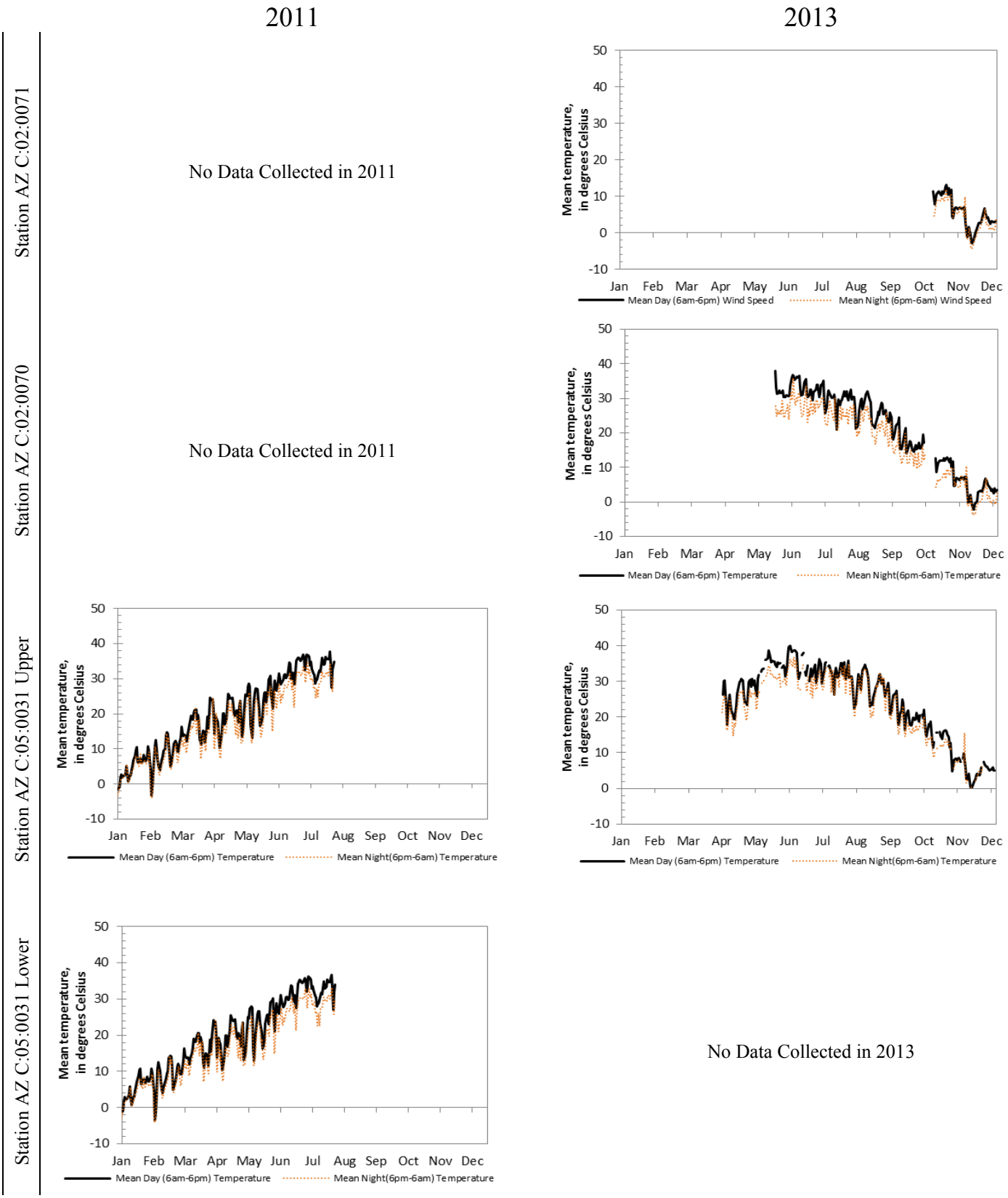


Figure 6. Graphs showing mean air temperature recorded for 12-hour day (6 a.m.–6 p.m.) and night (6 p.m.–6 a.m.), January 1, 2011, through December 31, 2013. Data were not collected between November 22, 2011, and April 27, 2013.

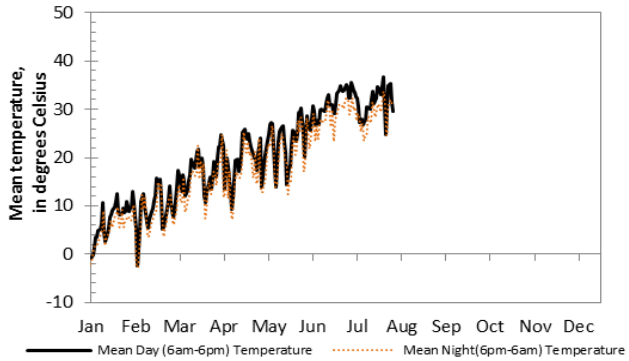
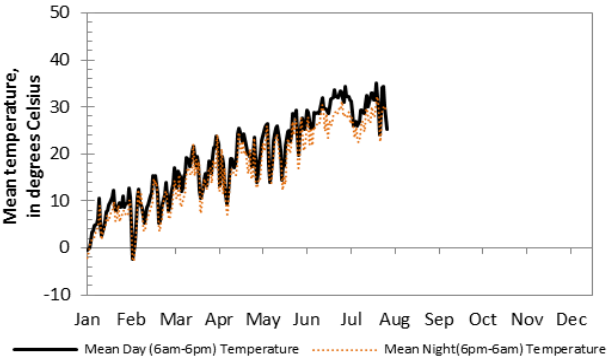
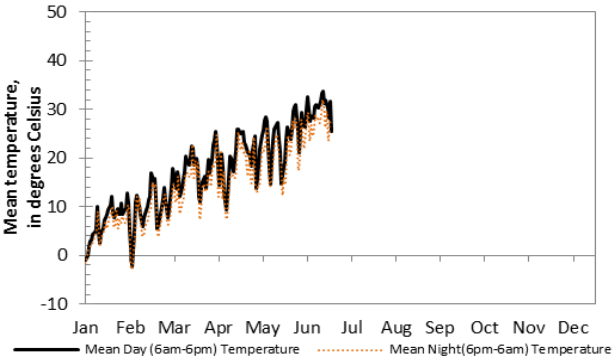
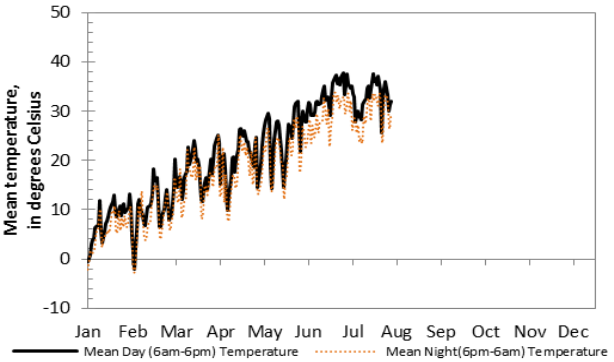
	2011	2013
Station AZ C:13:0365 Upper		No Data Collected in 2013
Station AZ C:013:0365 Lower		No Data Collected in 2013
Station AZ C:013:0006		No Data Collected in 2013
Station AZ C:013:0336		No Data Collected in 2013

Figure 6.—Continued

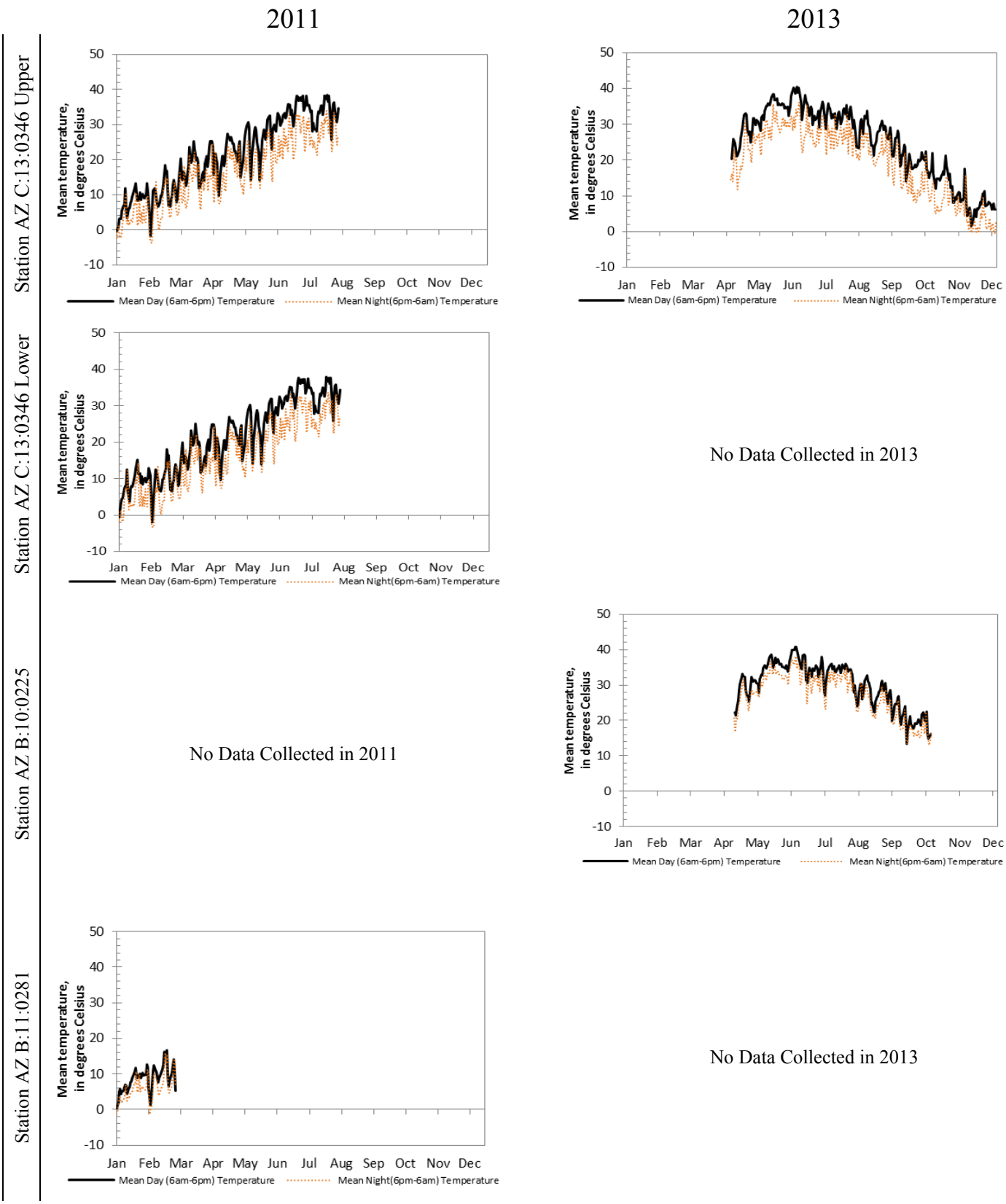


Figure 6.—Continued.

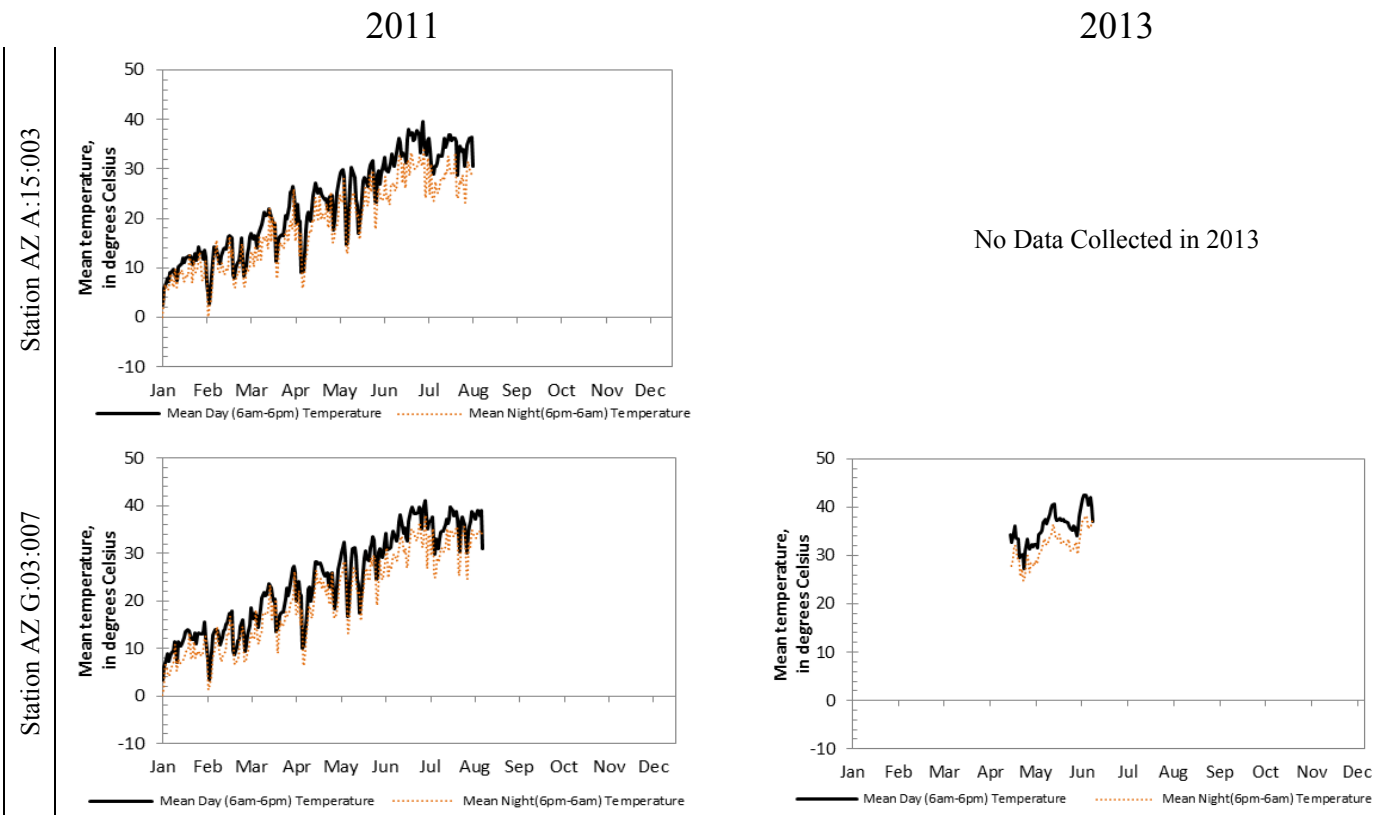


Figure 6.—Continued

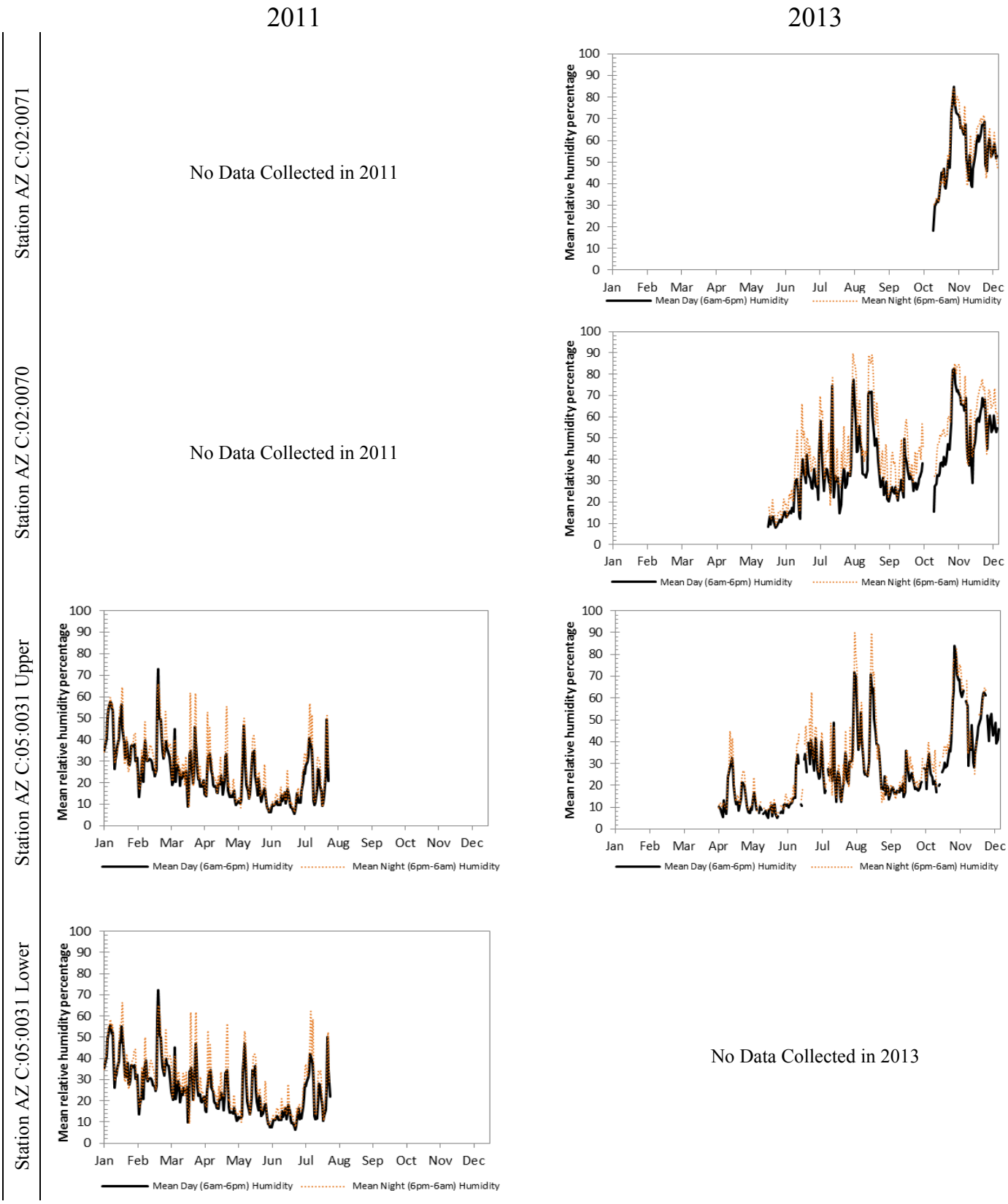


Figure 7. Graphs showing mean relative humidity recorded for 12-hour day (6 a.m.–6 p.m.) and night (6 p.m.–6 a.m.), January 1, 2011, through December 31, 2013. Data were not collected between November 22, 2011, and April 27, 2013.

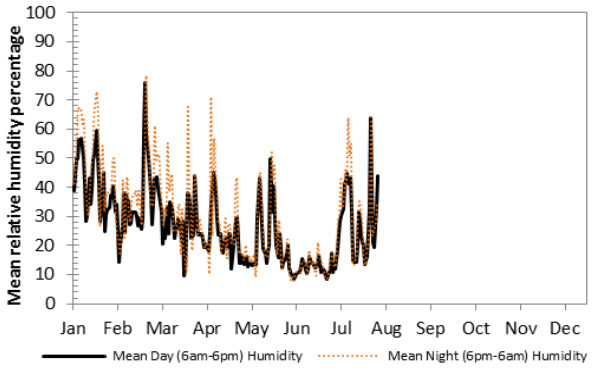
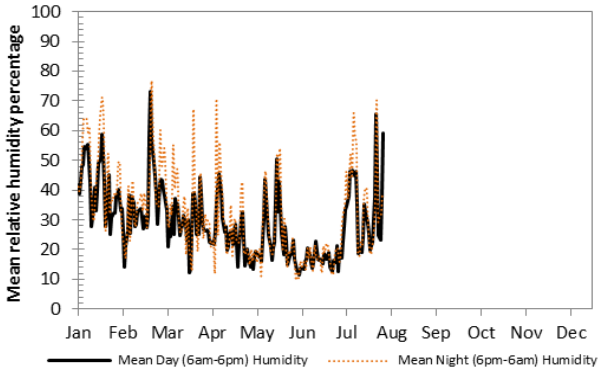
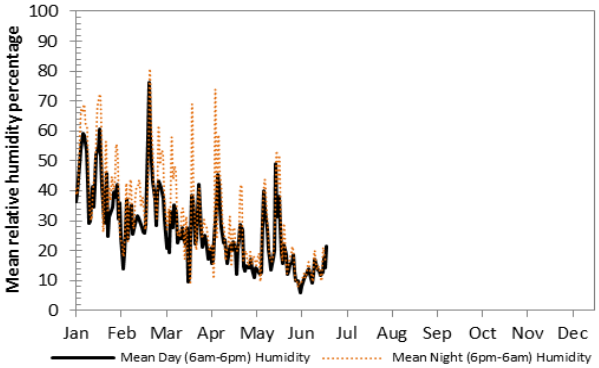
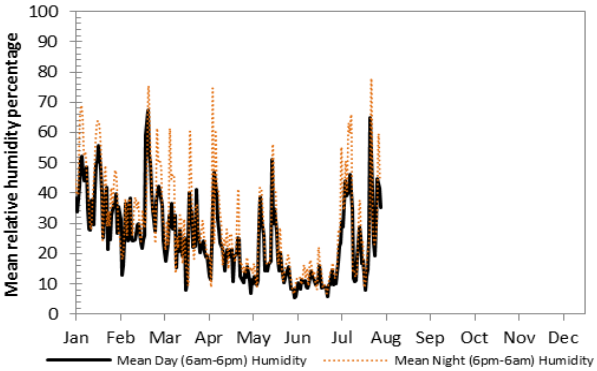
	2011	2013
Station AZ C:13:0365 Upper		No Data Collected in 2013
Station AZ C:013:0365 Lower		No Data Collected in 2013
Station AZ C:013:0006		No Data Collected in 2013
Station AZ C:013:0336		No Data Collected in 2013

Figure 7.—Continued

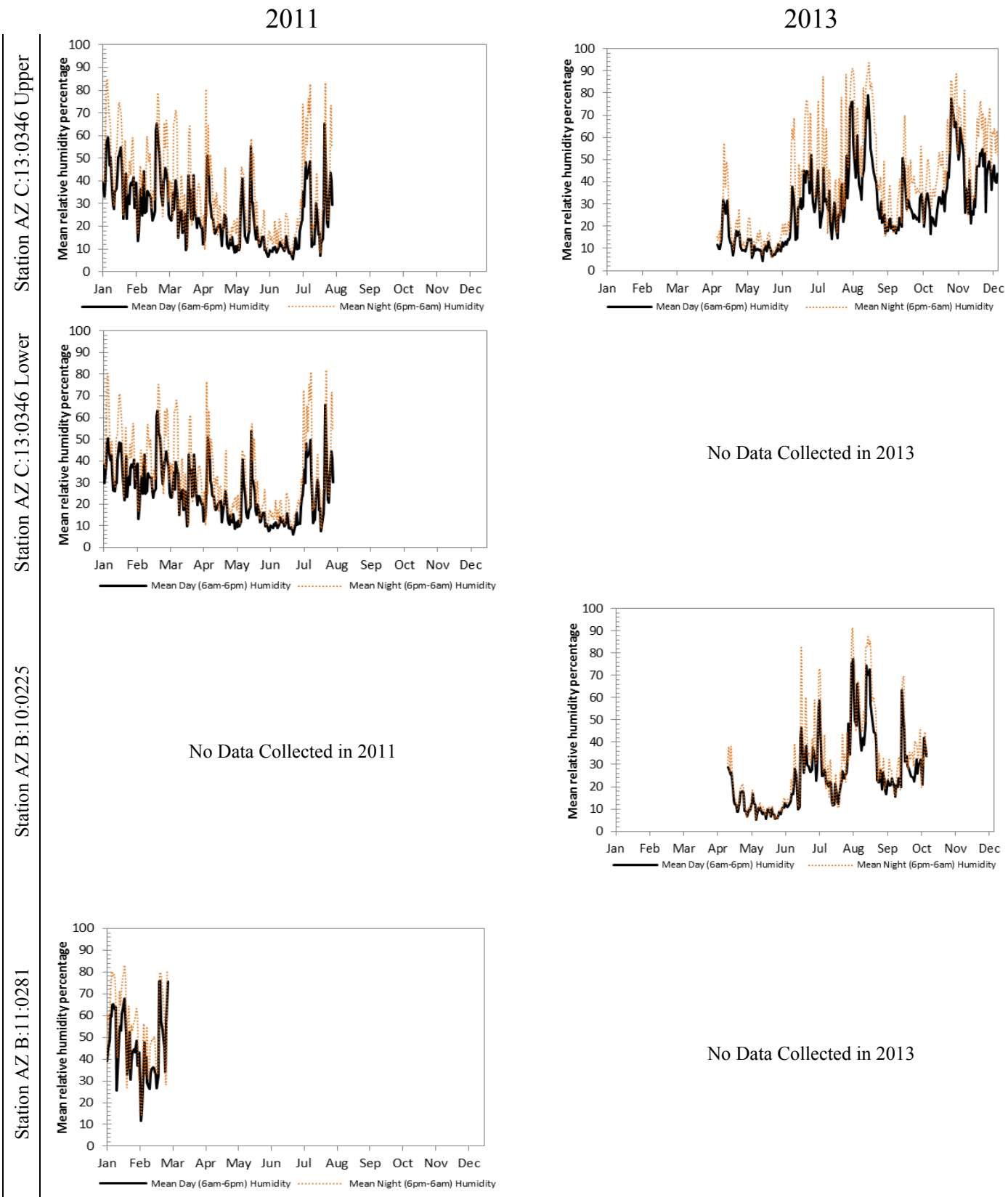


Figure 7.—Continued

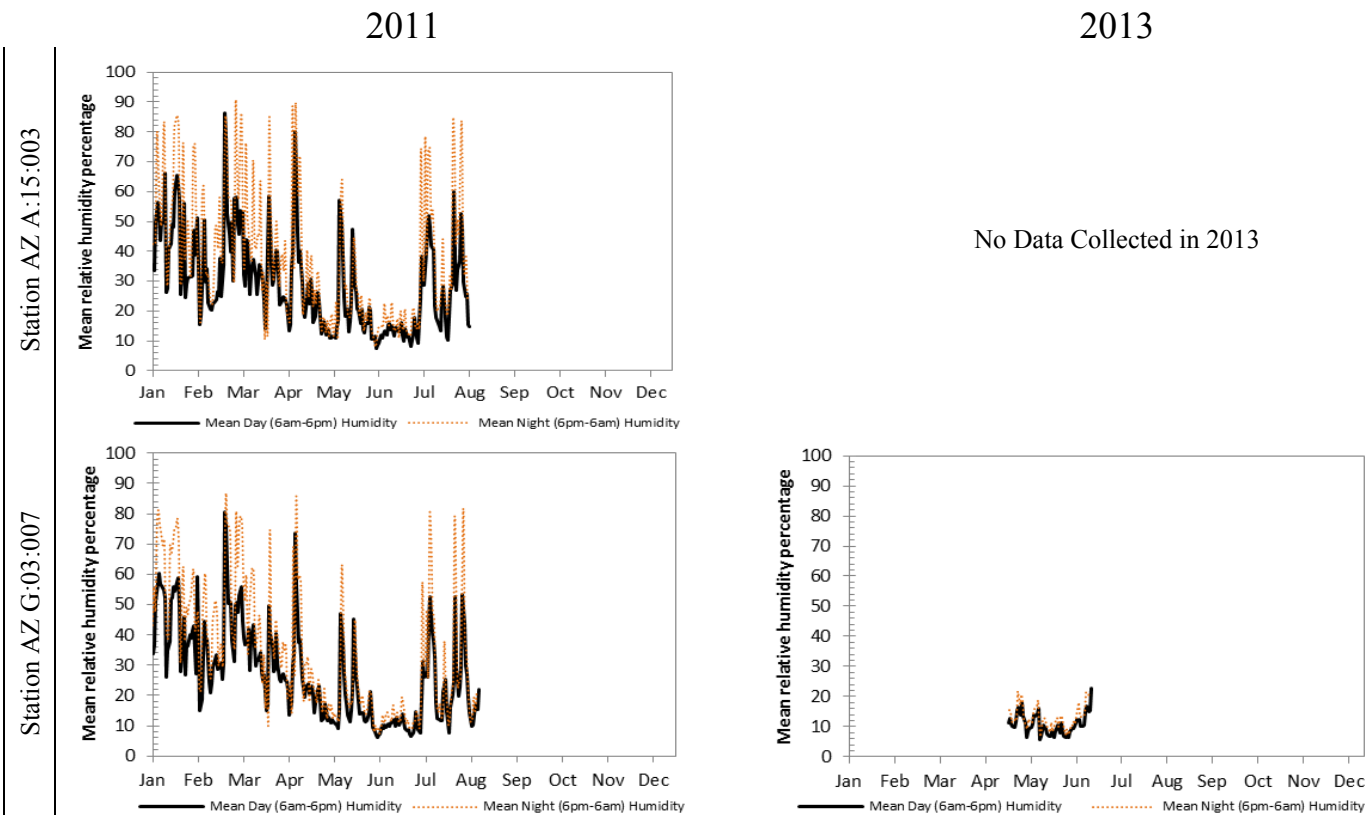


Figure 7.—Continued

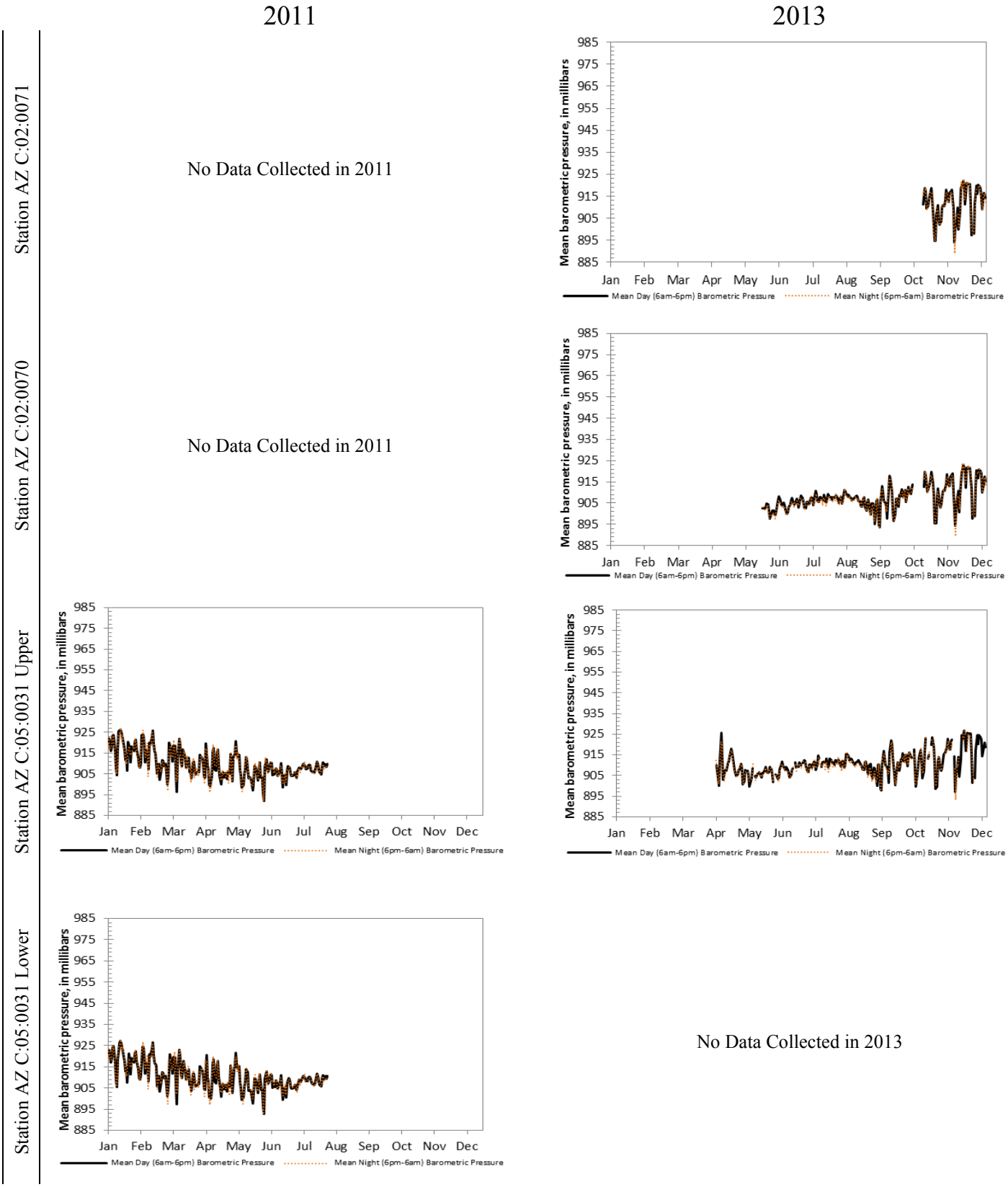


Figure 8. Graphs showing mean barometric pressure recorded for 12-hour day (6 a.m.–6 p.m.) and night (6 p.m.–6 a.m.), January 1, 2011, through December 31, 2013. Data were not collected between November 22, 2011, and April 27, 2013.

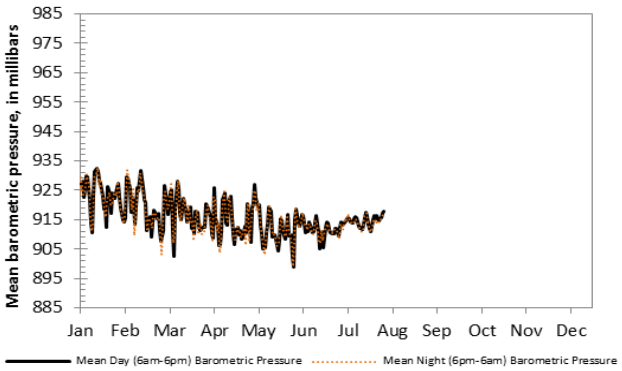
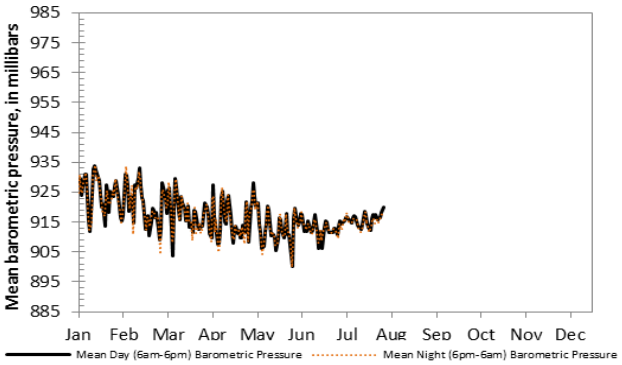
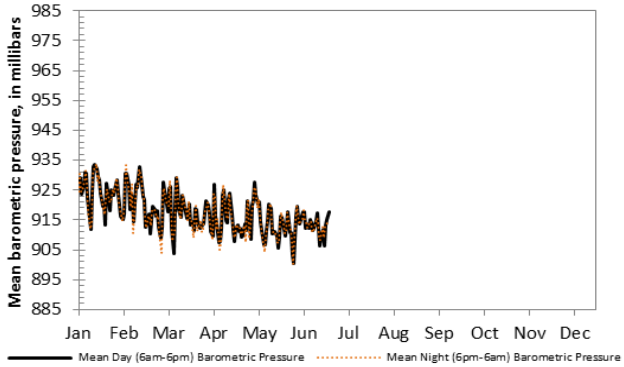
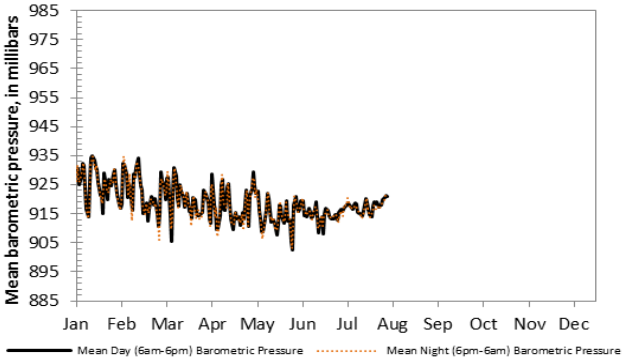
	2011	2013
Station AZ C:13:0365 Upper		No Data Collected in 2013
Station AZ C:013:0365 Lower		No Data Collected in 2013
Station AZ C:013:0006		No Data Collected in 2013
Station AZ C:013:0336		No Data Collected in 2013

Figure 8.—Continued

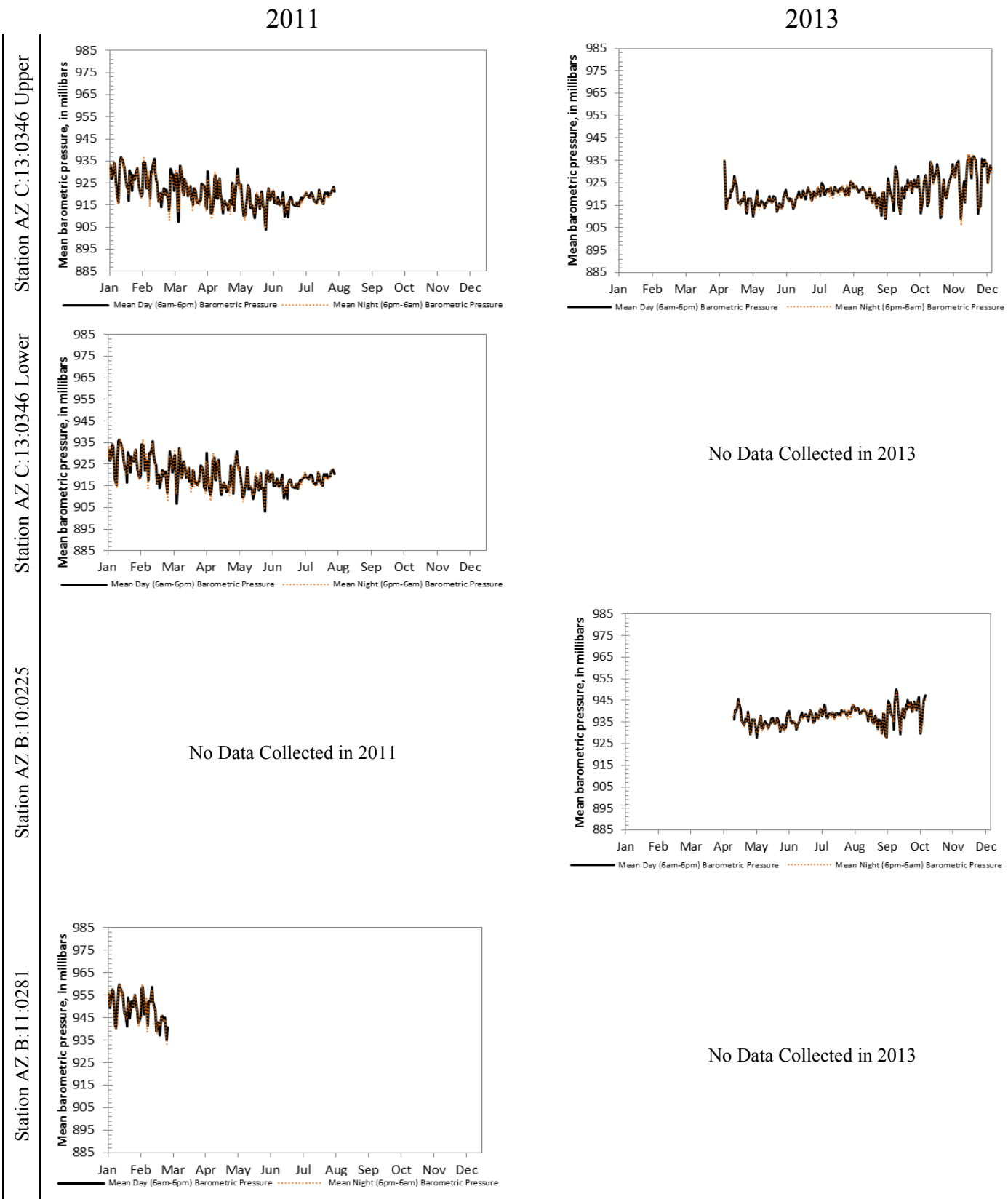


Figure 8.—Continued

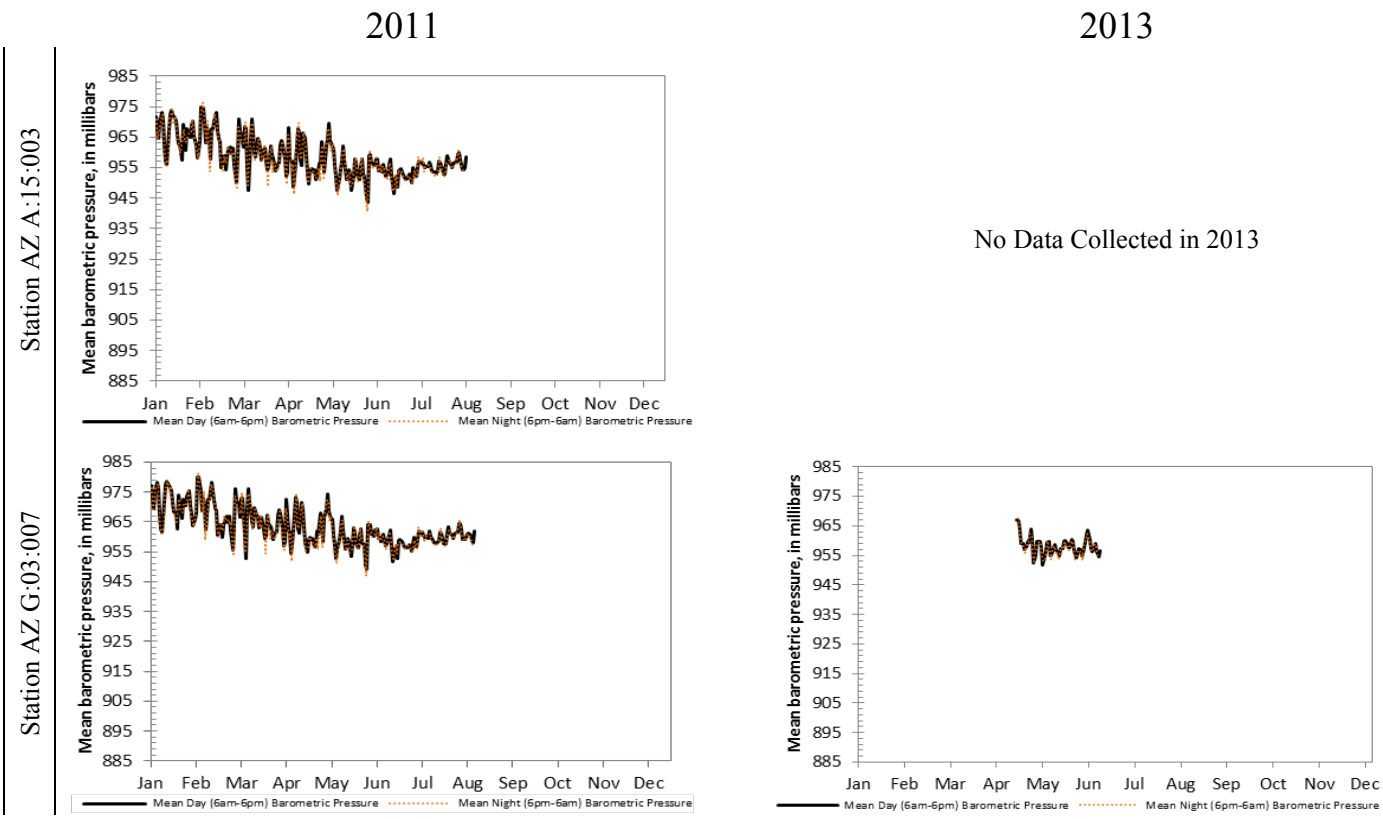


Figure 8.—Continued

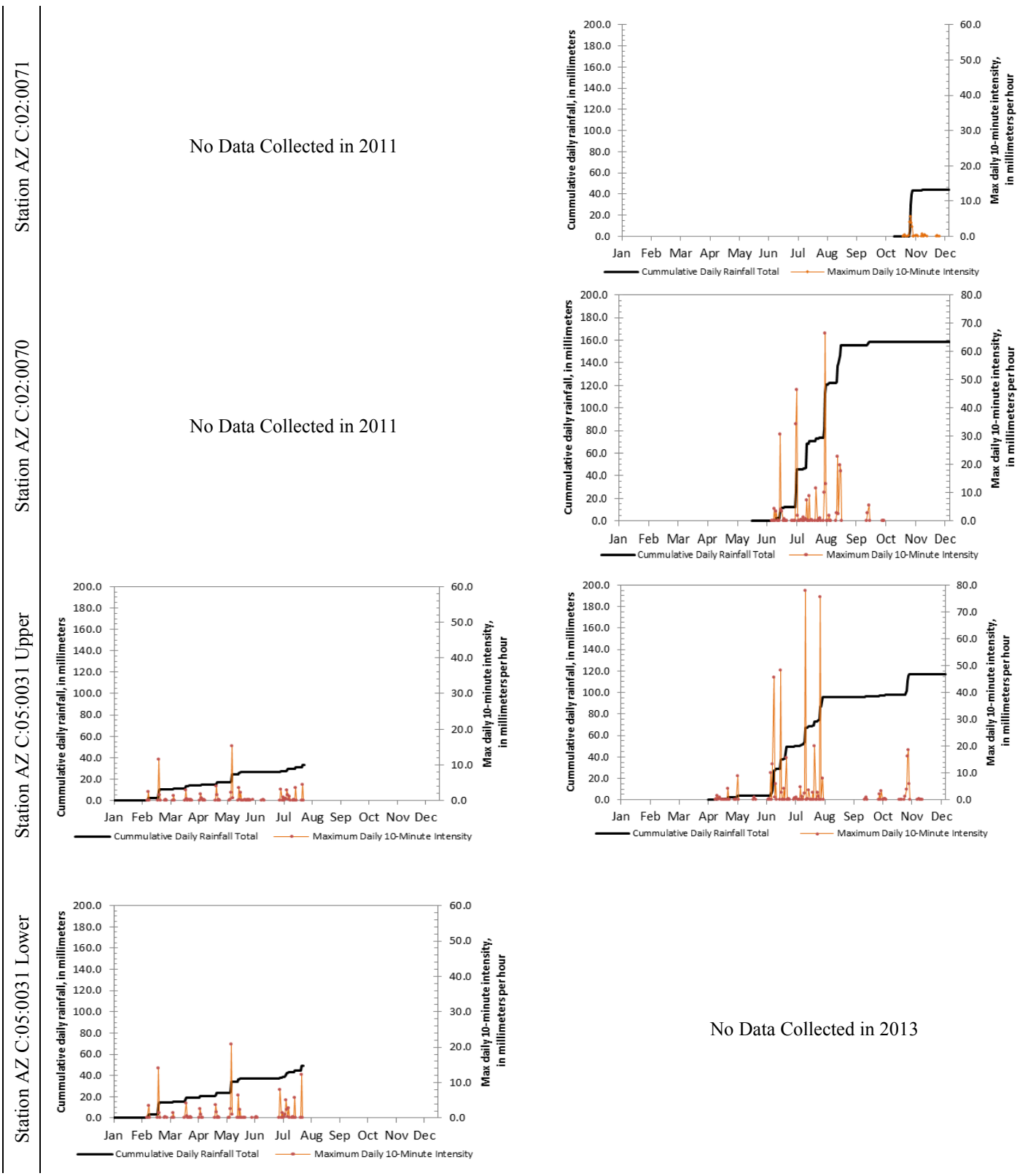


Figure 9. Graphs showing cumulative daily rainfall and maximum daily 10-minute precipitation intensity, January 1, 2011, through December 31, 2013. Data were not collected between November 22, 2011, and April 27, 2013.

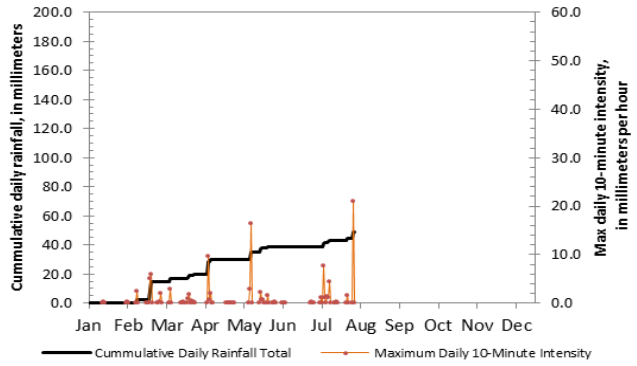
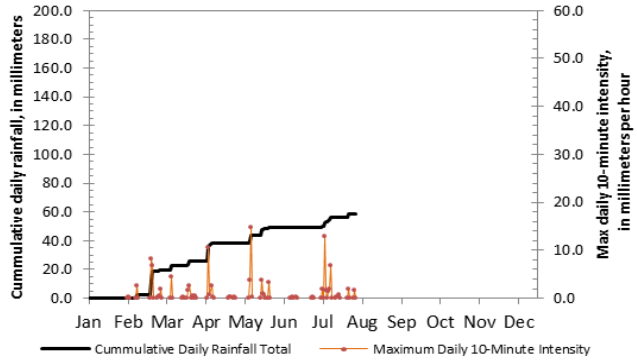
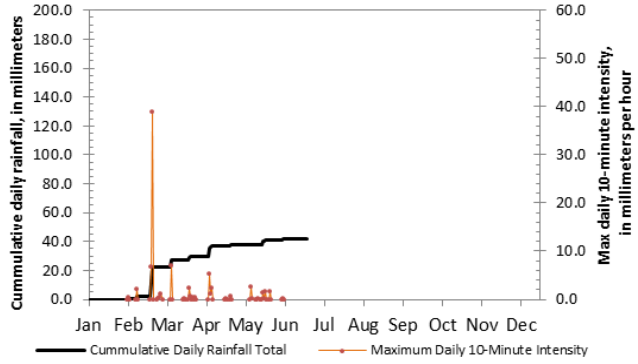
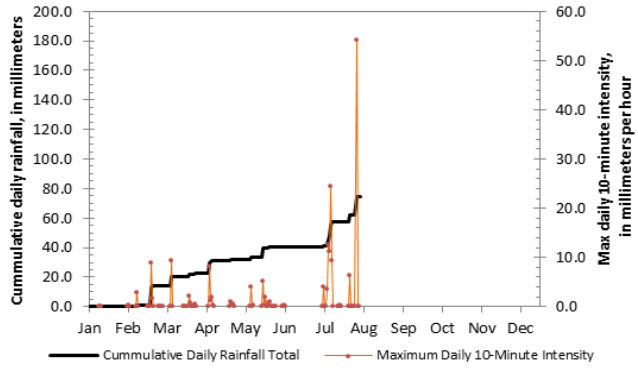
	2011	2013
Station AZ C:13:0365 Upper		No Data Collected in 2013
Station AZ C:013:0365 Lower		No Data Collected in 2013
Station AZ C:013:0006		No Data Collected in 2013
Station AZ C:013:0336		No Data Collected in 2013

Figure 9.—Continued

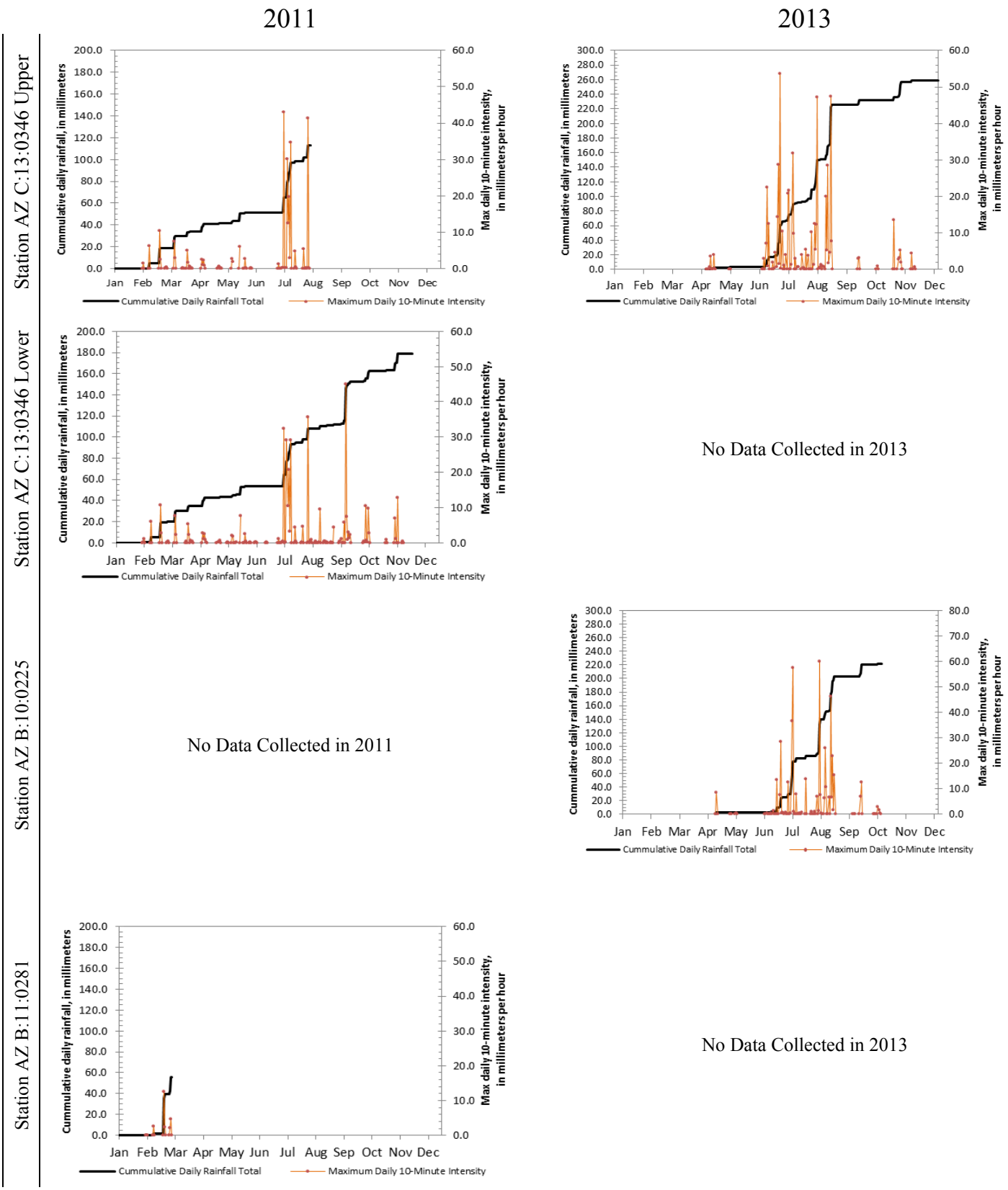


Figure 9.—Continued

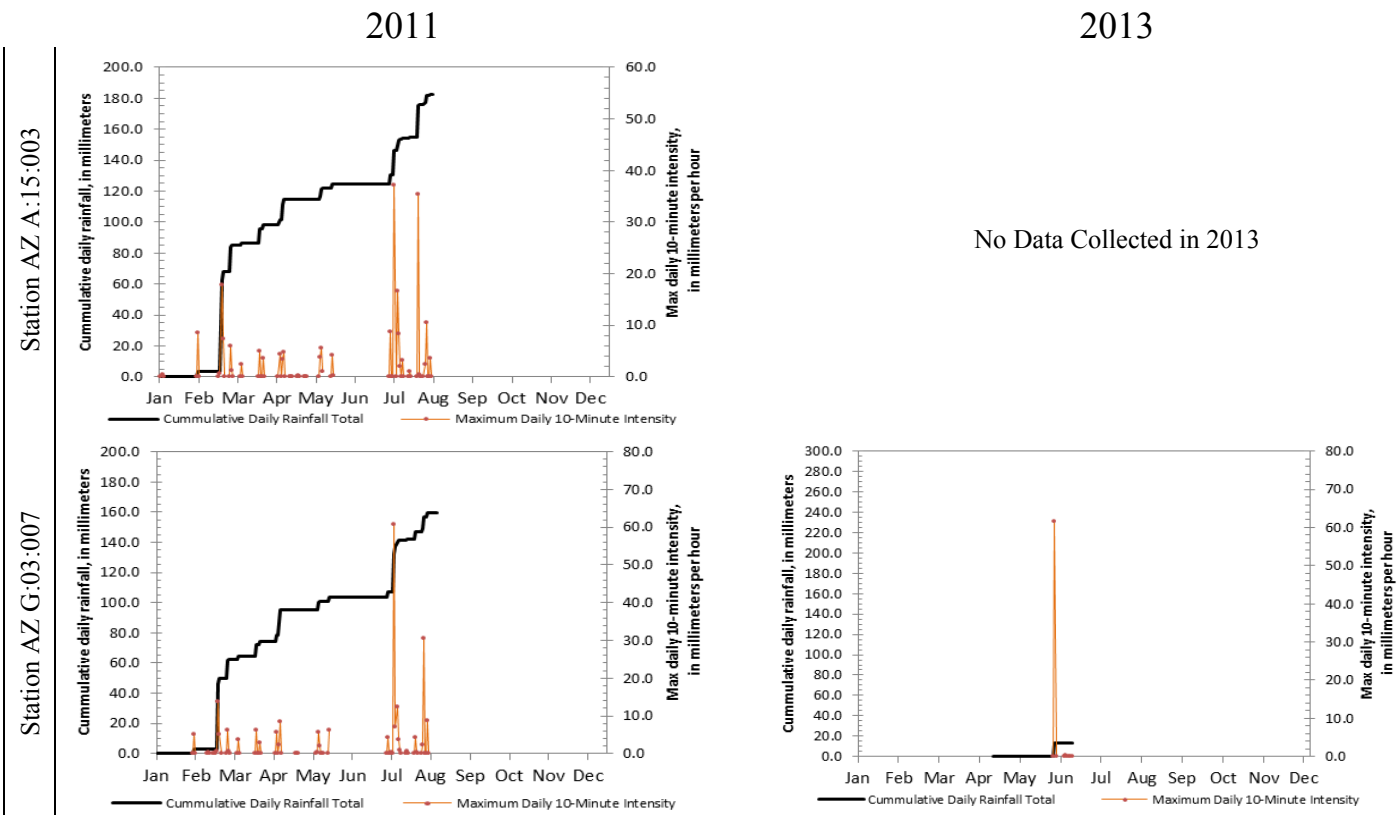


Figure 9.—Continued

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Appendixes

Appendixes 1 and 2 are Microsoft® Excel files that can be downloaded from *http://pubs.usgs.gov/of/2014/1247*. Appendixes 3 and 4 are Microsoft® Excel files or Comma-separated value (CSV) files that can be downloaded from *http://pubs.usgs.gov/of/2014/1247*.

Appendix 1. Explanation of Data Gaps within the Recording Period

Appendix 2. Potential Errors Identified during Quality Assessment

Appendix 3. Meteorological Data for Seven Weather Parameters, Glen Canyon Recreation Area, Arizona, January 2011—December 2013

Appendix 4. Meteorological Data for Seven Weather Parameters, Grand Canyon National Park, Arizona, February 2007—December 2010

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