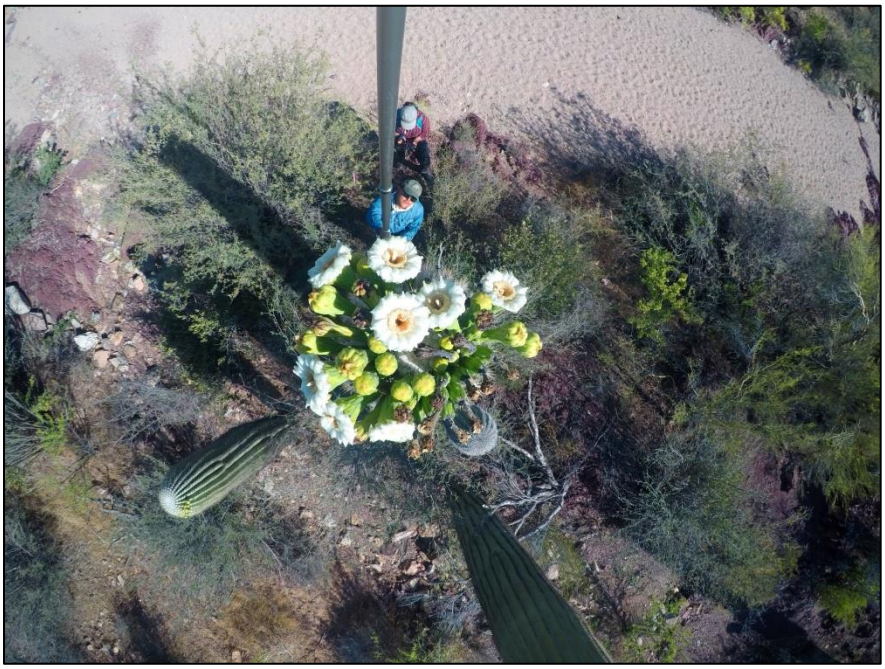
Is the timing of saguaro flowering changing?

Using citizen science to understand changes in saguaro phenology



Next Gen intern Lupe Sotelo and citizen scientist volunteer Blu Au collecting saguaro flower data for the saguaro phenology study, using a digital camera mounted on a telescoping "selfie stick". NPS photo, 28 April 2020.

Final Report to Western National Parks Association, Grant #19-07

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EXECUTIVE SUMMARY

The saguaro cactus is a keystone species in the Sonoran Desert, supporting >100 species of animals. Some evidence suggests that warmer temperatures are causing saguaros to bloom earlier than in the past, which may affect sensitive plant-pollinator relationships. With the assistance of citizen scientists, we collected daily saguaro phenology data during the reproductive seasons of 2017-2020 in the west district of Saguaro National Park. We used digital photography to photograph buds, flowers, and fruit on approximately 80 stems to investigate the pattern and mechanism for the seasonal changes in orientation of flowers and buds. Flower initiation occurred earlier in 2017 and 2018 than in 2019 and 2020, and regression models indicated that the number of daily saguaro flowers responds directly to solar radiation and temperature. Although we have only observational data from the park in the past, evidence from our study suggests that saguaros are blooming earlier than a few decades ago. We also quantified the novel finding that buds and flowers appear in spring first on the east side of the saguaro crown, then appear in counterclockwise succession on the north, west, and southern sides. Our study provides Saguaro National Park with a better understanding of the relationship between climate change and saguaros. As this long-term study continues, we will further investigate how specific climatic factors determine a range of saguaro reproductive responses. WNPA support provided the opportunity not only to support this research but also to create social media posts that engaged the park's digital visitors on a weekly basis during the saguaro reproductive season, which was well-received during the Covid-19 pandemic.

INTRODUCTION

Temperatures in the Sonoran Desert are rapidly increasing, especially during the winter and spring (Weiss and Overpeck, 2005). The average temperature in Saguaro National Park is now 1.6^{o}F warmer than a century ago (Gonzalez et al. 2018). A key finding of the 2018 Fourth National Climate Assessment is that the rising temperatures are altering plant phenology. Across much of the United States, plants are leafing and producing flowers earlier in the year compared to 20th-century averages (Lipton et al. 2018). Bowers (1996) estimates that flowering dates of Sonoran Desert shrubs may have advanced by 20-41 days during the past century.
Saguaros and other succulent plants that store water respond differently to phenological cues than other plants. In their study of Finger Rock Canyon in Tucson, Crimmins et al. (2010) found that the first saguaro bloom date has shifted three days earlier during the past 20 years and is significantly correlated with precipitation from the previous December. In a 22-year study of 11 saguaros on Tumamoc Hill, Bowers (1996) found that the phenological trigger for saguaro budding is a complex interaction between precipitation, temperature, and solar radiation. The initial triggers are a precipitation event of at least 5-9 mm and a photoperiod of 10.5 hours. Solar thermal units (daily mean temperature × total daily solar radiation) above a base temperature of 10^{o}C must accumulate to about 489,500 for half the saguaro population to flower. More recently, Renzi et al (2019) found that warmer temperatures were correlated with earlier flower onset and higher bloom yields, while increased rain appeared to delay onset and reduce flower numbers.

This study further investigates the complex relationship between saguaro phenology, climate, and saguaro height, using a novel technique based upon digital photography. Our first objective was to develop statistical models of saguaro phenology in order to estimate saguaro flowering dates for previous years in which observations are not available. Our second objective was to study the location and survival of buds and flowers on the saguaro crown. Johnson (1924)

observed that buds (and subsequent flowers) occurred first on the east and east-southeast side of the crown before other areas, and that most flowers on the northern part of the crown do not survive. Our preliminary observations suggested that location of buds and flowers was more nuanced than he described.

METHODS

Saguaro Phenology (Objective 1). In 2017, we established a study plot near the Red Hills Visitor Center in the Tucson Mountain District (TMD) of the park, at an elevation of approximately 2,500 feet (762 meters). We recorded the height, number of stems, and GPS coordinates of 55 saguaros with heights >2 m (the approximate height of first reproduction; Steenbergh and Lowe 1983), and <8 m (the length of our photographic pole). To photograph saguaro crowns, we attached a Nikon digital camera to a PVC pipe mounted on top of an extendable flagpole. The camera was connected to a handheld tablet via the Wireless Mobile Utility application, so that the tablet holder had a live view of what the camera lens was capturing (Figure 1).

Saguaro flowering in TMD typically begins around the last two weeks of April (Steenbergh and Lowe 1983). Flowers open shortly after nightfall, remain open through morning, and attract a range of pollinators including bees, white-winged doves and other birds, and nectar-feeding bats (Fleming 2000). In our study interns and volunteer citizen scientists photographed the crown of the main stems and all the arms 6 days/week from about 600-800h local time. Except for 2017, we began photographing the saguaros the first week in April and continued through the middle of July, so that we could capture the entire budding and flowering reproductive season. During the 2020 season, which started in early April as the country was responding to the Covid-19 pandemic, we created three two-person, socially-isolated teams and instituted a strict safety protocol that included disinfecting of all equipment at the beginning and end of each survey.

Saguaro Bud and Flower Orientation (Objective 2). For bud-flower orientation, we selected a subset of 20 saguaros and confined our analysis to the crown of the main stem, because saguaro arms may twist in response to environmental factors. We created reference photos by photographing each saguaro with a line on the ground that was oriented to magnetic north with a compass. We overlaid a transparent digital compass on each photo to correct for a declination of +9° 35' positive east. The digital compass divided the saguaro crown into 12 sectors: N, NNE, ENE, E, ESE, SSE, S, SSW, WSW, W, WNW, and NNW.

Thermal Photography. Instead of digital temperature loggers to measure crown temperatures, as originally planned, we learned of a more accurate method using digital infrared cameras that could provide greater coverage of the saguaro crown. We refined the method during the 2019 season and implemented it in 2020, mounting the camera on a platform with a uniform-color background to equalize temperature (Figure 1). To determine how crown and side temperatures varied in time, we collected data 1-2 days/month at 1-hour intervals from sunrise through sunset.

Photographic Analysis. For the saguaro phenology objective, we reviewed daily photos for all 55 saguaros and counted the flowers on the main stem and all arms. If photographs for a given day were of poor quality or not available, we used the next day's photo to determine the flower count. One-day old flowers appear slightly open, often with some of the white petals still visible, and 2-day old flowers have a textured-yellow top (Renzi et al. 2019).

For the bud and flower orientation objective, we used a subset of data from 20 saguaros during 2017-2018. For each compass sector and day, we counted the total number of open flowers and recorded the presence (1) or absence (0) of buds, which vary greatly in size and are difficult to count accurately. Because buds and flowers can be up to 12 cm in length and sometimes bend, we assigned them to the sector where the base was located. When photographs were not available, we determined bud locations using photos from the day before and the day after. To evaluate the statistical significance of the circular datasets, we used the circular chi-squared goodness of test (Watson 1987), which is very similar to the linear version. The null hypothesis is that the distribution around the circle is uniform, with the expected value in each sector approximately equal to the total number of flowers or buds divided by the number of sectors.

Statistical Analysis of Saguaro Bud Data

To analyze the correlation between daily flower abundance and meteorology, we created a stepwise regression model based on 2017-2019 daily minimum temperature, maximum temperature, and precipitation data from the weather station in the Red Hills Visitor Center (https://www.ncdc.noaa.gov/cdo-web). The nearest weather station measuring daily total solar radiation is located at the University of Arizona agricultural center in Tucson. The station is part of the Arizona Meteorological Network (AZMET; https://cals.arizona.edu/azmet).

RESULTS AND DISCUSSION

Saguaro Phenology. A century ago, Johnson performed his study at the Desert Laboratory on Tumamoc Hill, located approximately 20 km northwest, and at a similar elevation (approximately 800 m) to our study plot. At the same location, from Bowers (1996) tracked the flowering of 10-11 saguaros (17-18 stems) from 1968 through 1988. Bower's average flowering date (the first day when 50% of the saguaros are blooming) was 19 May. Our average flowering dates were earlier in 2017 and 2018, the same in 2020, and later in 2019 (Table 1). Bowers obtained an average flower initiation date of 8 May, and all our initiation dates were earlier. Steenbergh and Lowe (1983) observed that flower initiation begins sometime during the last two weeks of April (16-30 April). Except for 2018, our first flowering dates fall within the beginning of Steenberg and Lowe's range (Figure 2). We will be continuing our saguaro phenology research in 2021 to obtain more observational data.

Table 1: Dates of first flower, average flower, and last flower.

Year	First Flower	Last Flower	50% Flower	n
2017	April 18	July 14	May 17	131
2018	April 5	July 17	May 11	125
2019	April 17	July 19	May 28	124
2020	April 20	July 20	May 19	124

Daily flower abundance compared to min-max temperatures (Figure 3) suggest that blooming occurred in all years during periods when temperatures are relatively constant. Daily flower numbers peak just before the temperature increases in June and decline rapidly afterwards. Peaks and troughs of daily flower abundance also show some correspondence to daily solar radiation (Figure 4). The stepwise regression models (Table 2) show that temperature and solar radiation

have significant effect on the daily flower count while precipitation was not statistically significant. The regression models explained about 10% of the variability associated with the daily flower count. After collecting a fifth season of saguaro phenology data in 2021, we plan to further explore the connections between reproductive, meteorological, and landscape variables such as slope and aspect.

Table 2: Stepwise regression models for daily flower abundance and meteorological parameters. For the coefficients, a value of zero means that the coefficient was not statistically significant. At the time of writing this report, the 2020 data was not yet available.

Regression Coefficients				Model Parameters			
Parameter	**2017**	**2018**	**2019**	**Parameter**	**2017**	**2018**	**2019**
Precipitation	0.0	0.0	0.0	Correlation coefficient	0.329	0.316	0.339
Maximum temperature	-1.6	0.0	0.0	R-squared	0.108	0.100	0.115
Minimum temperature	0.0	0.0	-1.6	Root mean square error	59.1	91.8	56.4
Solar radiation	4.6	6.0	3.3	p-value	0.005	0.004	0.002
Intercept	72.0	-104.2	58.6	Number of values	97	81	101

Bud and Flower Compass Orientation. Figure 5 shows the highly significant directional trend of the 2018 flower data based on 4-day intervals. Consistent with the observations of Johnson (1924), flowers appear first in the eastern sectors of the crown, then sequentially in the northern, western and southern sectors. Chi-squared values for the radar plots in Figure 5 are highly significant, with all but one period having a p-value of 0.025 or less. The 2017, 4-day bud data (not shown) showed the same trend with all but two periods having a p-value of 0.025 or less. In contrast to Johnson's statement that buds on the north side of the crown do not mature, we found that over the entire 2017 and 2018 seasons, both buds and flowers were most abundant on the north side (Figure 6; p=0.01 for buds and p= 0.001 for flowers). Thermal photography (Figure 7) revealed that the eastern and northern sides of the saguaro crown not only receives a greater heat load than other areas of the crown in the early morning hours, but remained warmer throughout most of the day, suggesting that warmer crown temperatures may play an important role in the location of buds and flowers.

CONCLUSION

The discovery that saguaros bud and flower first in the eastern part of the crown, followed by buds and flowers appearing in a counterclockwise direction to the north, west, and south, is a novel finding made possible by our digital photography technique. Saguaros may be unique among cacti in this seasonal movement of flowers, which we speculate may be the result of the thermal balance they must achieve as the most northern of columnar cacti, adapted to both cool winter and hot summer temperatures. By placing flowers on the east side of the crown in early spring they can take advantage of warmth, while placement of flowers on the west and south sides later in the season may minimize the effects of heat. Our thermal data tend to support this theory, but more research is needed. We have written a paper on this interesting and unique sequence of saguaro bud and flower direction that is currently in review.

The major goal of our study was to determine how environmental factors such as precipitation and temperature influence saguaro flowering phenology, and whether the timing of reproduction

may be changing as the Sonoran Desert gets warmer. The recently published paper by Renzi et al. (2019), based at a nearby site (Colossal Cave) that is higher in elevation and cooler than ours, suggest that warming temperatures are a major driving factor in causing saguaros to bloom earlier in the season. Our study is consistent with Renzi et al. (2019) and provides indirect evidence that saguaros are budding and blooming earlier then their phenology was studied by Johnson (1924), Steenbergh and Lowe (1983) and Bowers (1996). Renzi et al. (2019) suggests that these changes could impact pollen availability and pollinator population dynamics. We hope to explore this question collaboratively with them in a future paper.

INTERPRETIVE VALUE

Saguaro National Park was created in 1933 for its scientific and educational value related to the "remarkable giant cactus" and other unusual Sonoran Desert plants. An important goal of this study was to provide data to park managers for adapting to climate change, but engaging visitors in science is no less important. WNPA support allowed our "Next Gen" interns to create a large number of social media posts on Instagram and Facebook, including regular "#FlowerFrenzyFriday" posts during the 2020 season (Figure 8). These posts celebrated our citizen science volunteers and interns while keeping our digital audience up-to-date on the saguaro flower-fruit season and sharing with them photos and facts about many other related topics including flowers of other cacti, thermal ecology, wildlife use of flowers and fruit, and pollinators and pollination research.

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FIGURES

Figure 1. Left: photographing saguaro crowns with a digital camera mounted on a telescoping pole. Middle: An example of a photograph of a saguaro crown. Right: Frame and digital infrared camera to record crown temperatures seen in Figure 7. (NPS photos).

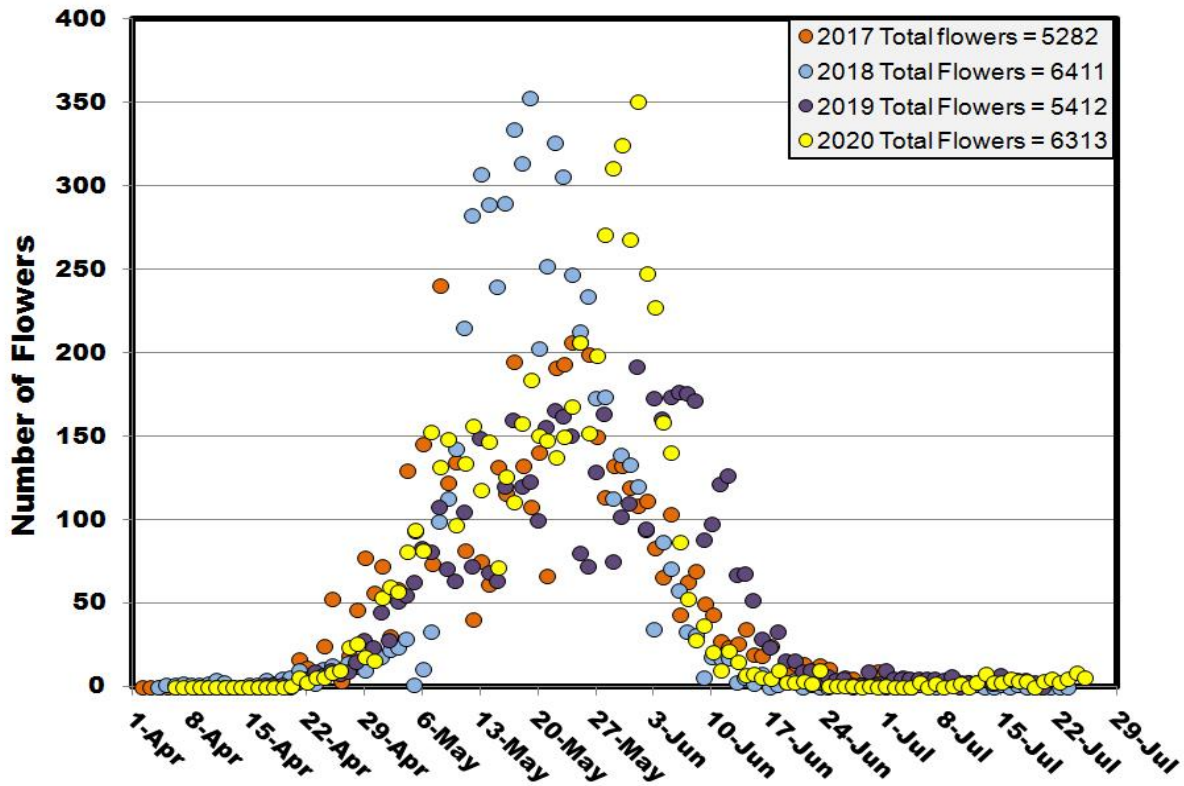


Figure 2. Daily number of flowers for each season, 2017-2020.

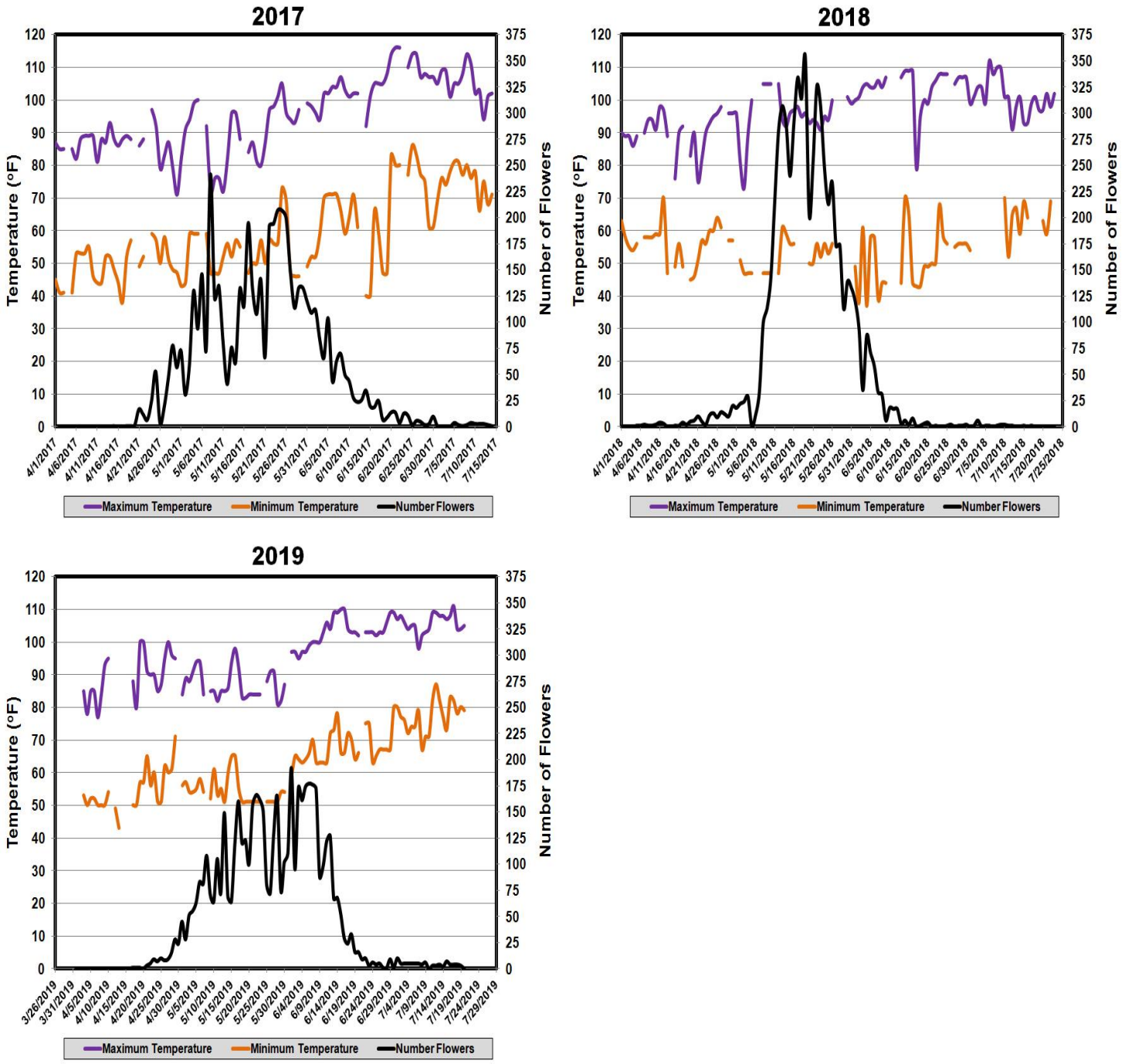


Figure 3. 2017, 2018. and 2019 daily flower abundance and temperature. Note that flowering peaks occur when temperatures are stable in early May, then fall as temperatures climb in late May to early June.

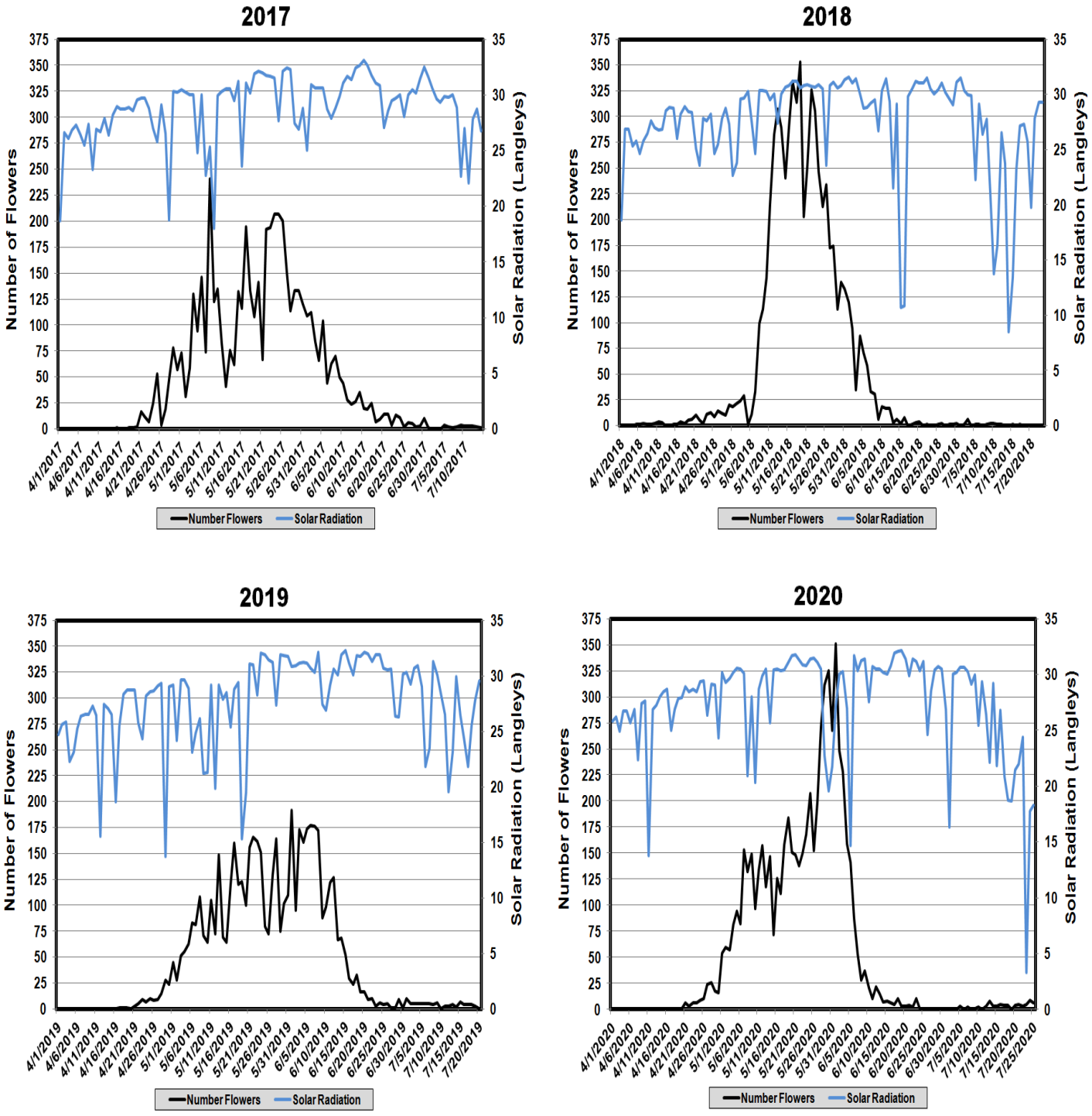


Figure 4. Daily solar radiation and flower abundance.

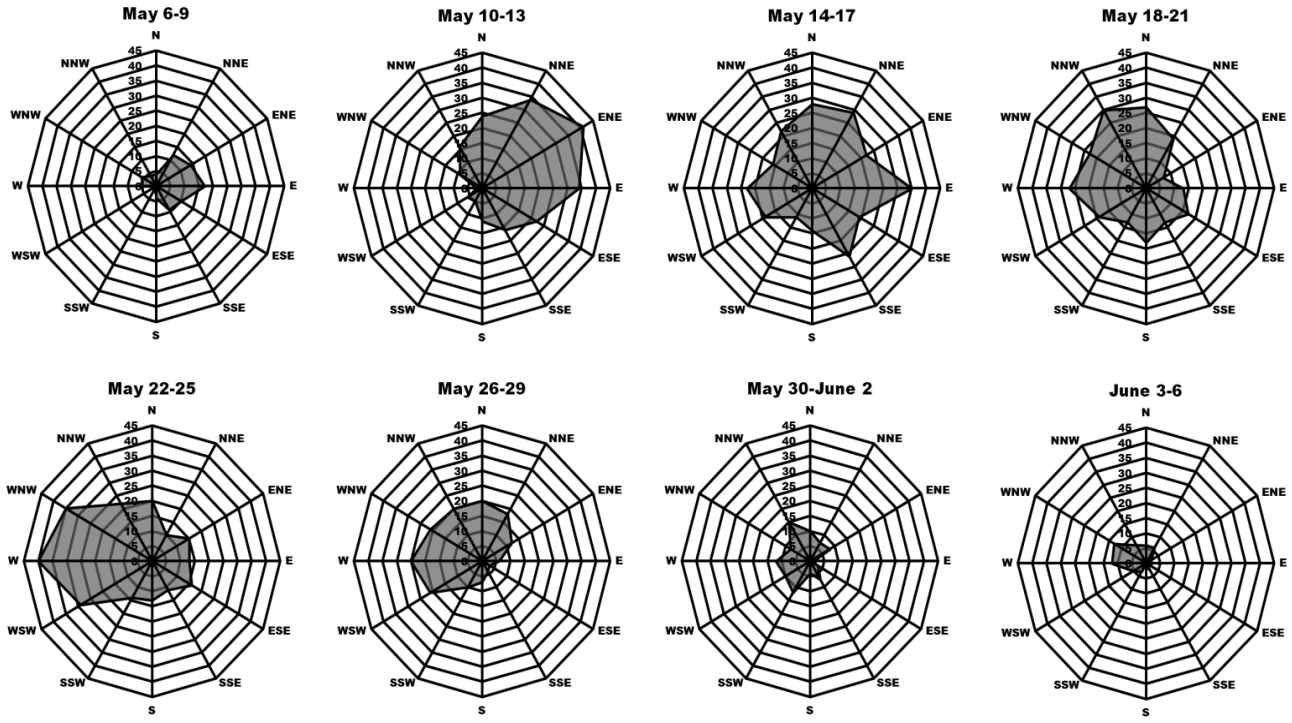


Figure 5: 2018 flower orientation of flowers in 4-day intervals, early May-early June. Note that flowers appear first in the eastern part of the crown, then in a counterclockwise succession.

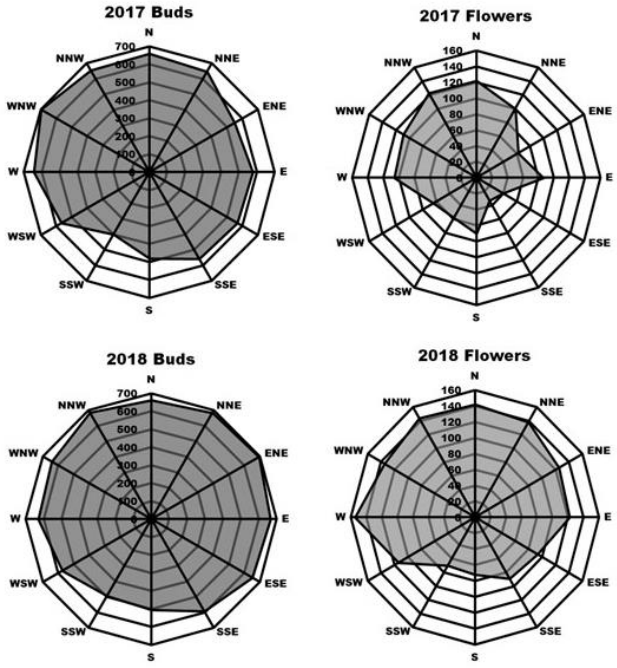


Figure 6. 2017 and 2018 bud and flower circular distributions. Although buds and flowers first appear in eastern part of crown (Figure 5), over the full season the distribution is highest in the north.

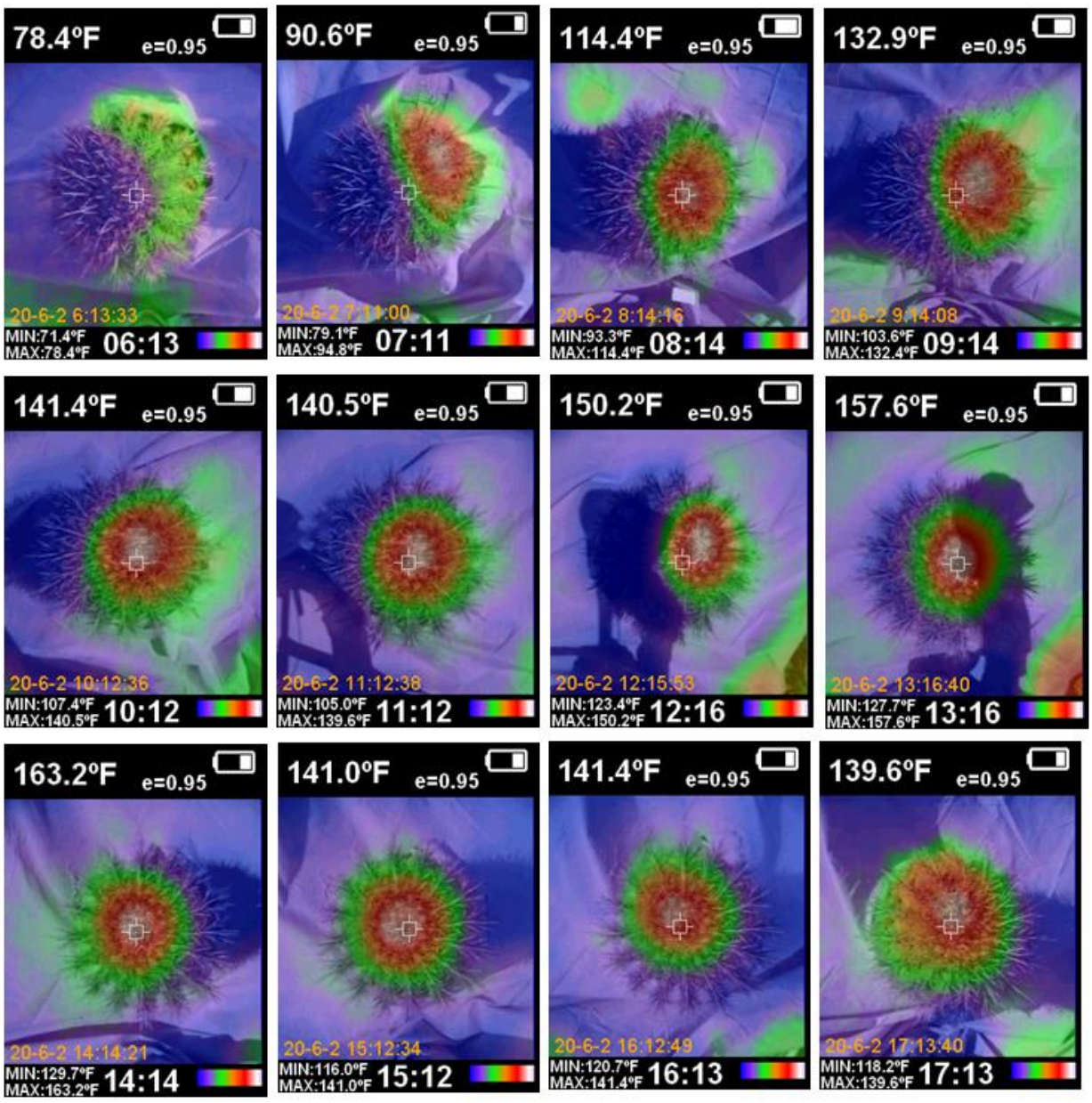
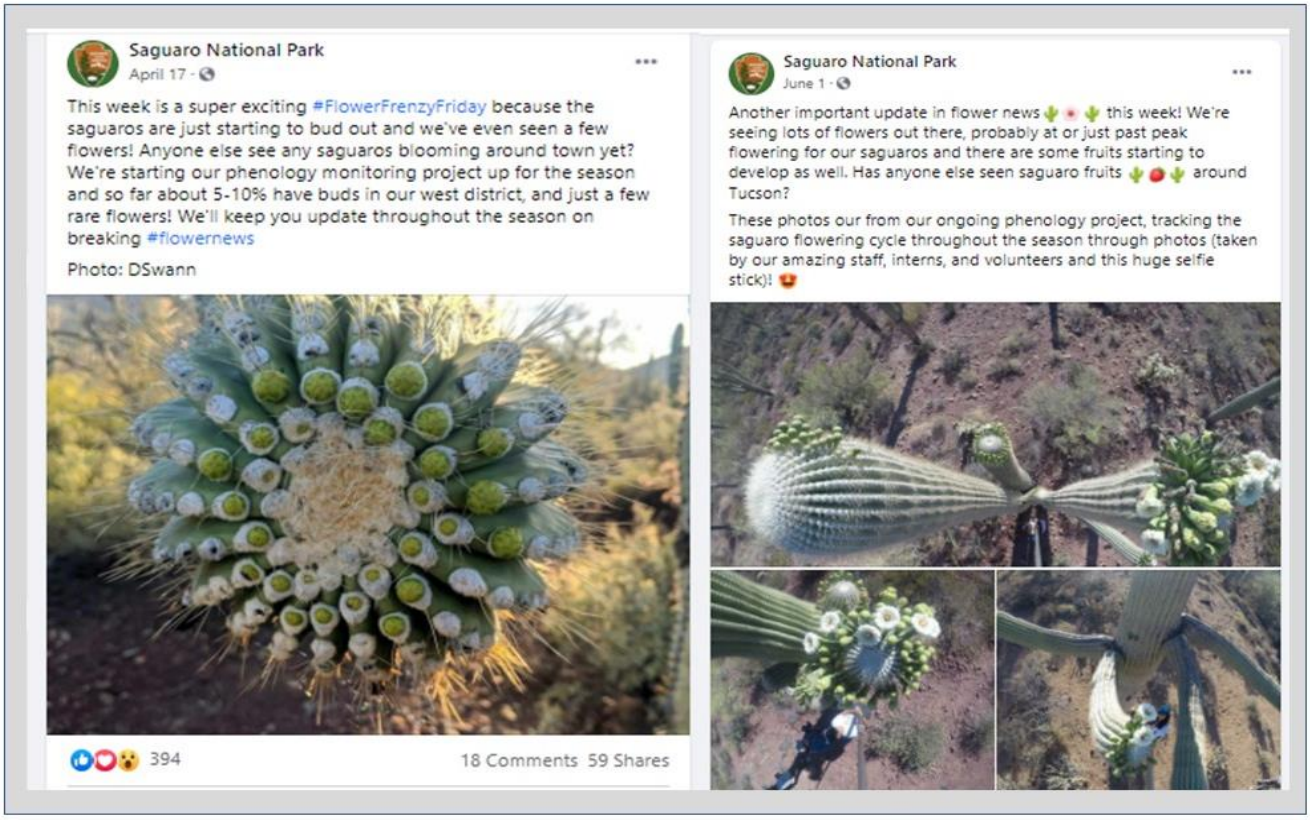


Figure 7. Typical daily time series of thermal radiation on saguaro crown, from sunrise to late afternoon, June 2 2020. These data consistently indicate that the east side of the crown receives the most heat early in the day, but also continues to stay warm through the entire day.



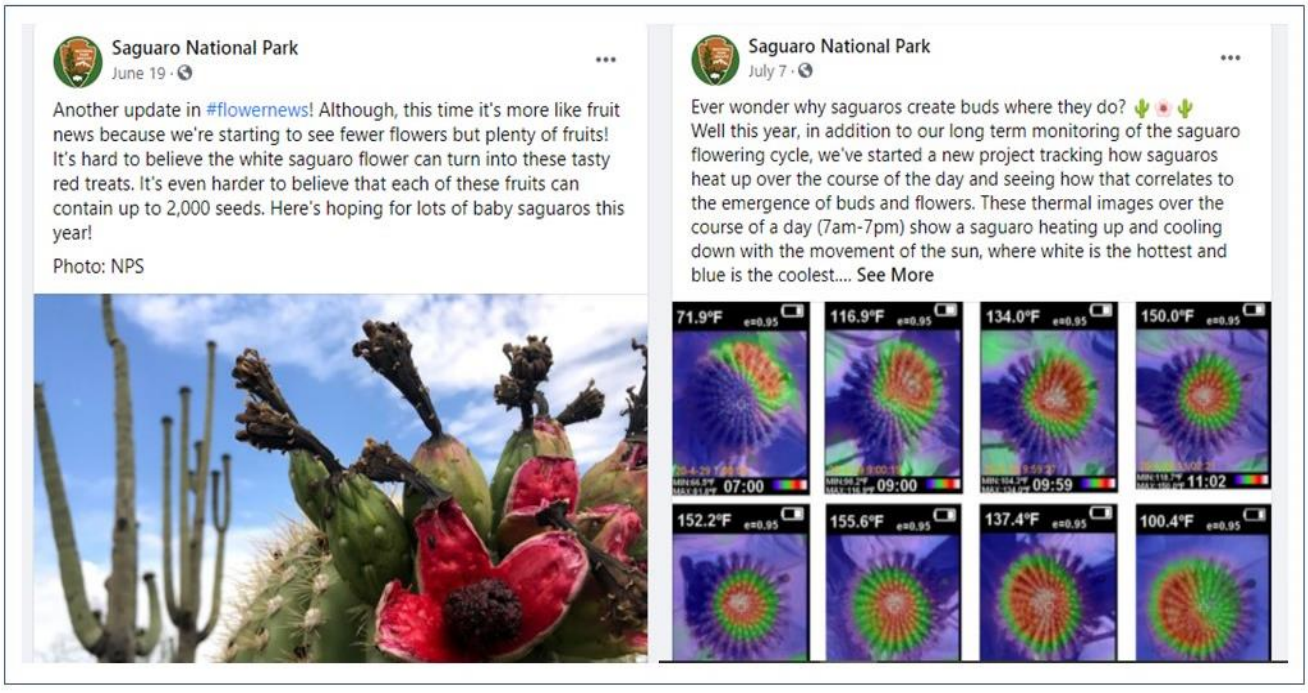


Figure 8. Examples of social media posts for #FlowerFrenzyFriday, 2020.